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Commentary

"Smart Is Not Smart Enough!" Anticipating Critical Raw Material Use in Smart City Concepts: The Example of Smart Grids

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Abstract: Globally emerging smart city concepts aim to make resource production and allocation in urban areas more efficient, and thus more sustainable through new sociotechnical innovations such as smart grids, smart meters, or solar panels. While recent critiques of smart cities have focused on data security, surveillance, or the influence of corporations on urban development, especially with regard to intelligent communication technologies (ICT), issues related to the material basis of smart city technologies and the interlinked resource problems have largely been ignored in the scholarly literature and in urban planning. Such problems pertain to the provision and recovery of critical raw materials (CRM) from anthropogenic sources like scrap metal repositories, which have been intensely studied during the last few years. To address this gap in the urban planning literature, we link urban planning literatures on smart cities with literatures on CRM mining and recovery from scrap metals. We find that underestimating problems related to resource provision and recovery might lead to management and governance challenges in emerging smart cities, which also entail ethical issues. To illustrate these problems, we refer to the smart city energy domain and explore the smart city-CRM-energy nexus from the perspectives of the respective literatures. We show that CRMs are an important foundation for smart city energy applications such as energy production, energy distribution, and energy allocation. Given current trends in smart city emergence, smart city concepts may potentially foster primary extraction of CRMs, which is linked to considerable environmental and health issues. While the problems associated with primary mining have been well-explored in the literature, we also seek to shed light on the potential substitution and recovery of CRMs from anthropogenic raw material deposits as represented by installed digital smart city infrastructures. Our central finding is that the current smart city literature and contemporary urban planning do not address these issues. This leads to the paradox that smart city concepts are supporting the CRM dependencies that they should actually be seeking to overcome. Discussion on this emerging issue between academics and practitioners has nevertheless not taken place. We address these issues and make recommendations.

Keywords: critical raw materials; smart city; smart grids; urban transition

1. Emerging Digital Technologies in Smart Cities

The last few decades have seen two major shifts concerning energy production and consumption. First, a rapid acceleration of renewable energy production technologies, including wind and solar technologies, has taken place (IEA 2018) and, related to this trend, new technologies for more efficient electricity consumption patterns have emerged (e.g., smart grids and smart metering), which are increasingly being installed on a global level [1]. These shifts are of particular importance for cities, as cities contribute 75% of carbon emissions from global final energy use [2]. The general narrative of these developments is that current urban energy production and consumption patterns need to be transformed in order to meet targets set in global sustainability agendas such as the Agenda 2030 or the Paris Agreement. The emerging concept of smart cities refers to smart energy and promises to have a direct impact on local sustainable development through the increased use of renewable energy and new technologies such as smart grids and smart metering [3–5].

It is challenging, and perhaps impossible, to capture these technological trends in exact numbers. Since the term smart city has no clear definition, it is understood as a broad assemblage of different instruments, practices, and sociotechnical innovations. Due to the terminological ambiguity, estimates on the exact global number of smart cities should be interpreted cautiously. However, smart cities are already being realized and attract huge revenue streams [6–8]. Different sources show dynamic emergence in practice: In 2012, Lee et al. [3] counted a total of 143 ongoing smart-city projects or completed self-designated smart-city projects worldwide and as early as 2014, the EU estimated that 90% of the cities with more than 500,000 residents were working on smart city approaches [9]. Recent developments, such as the 100 smart cities for India program [10], the 300+ smart city pilot studies in China [11], and the fact that 66% of US cities have invested in some type of smart city technology [12] demonstrate that the concept is gaining increasing significance in global urban development practices.

A central aspect of smart city applications is that they focus on efficiency in digitally based resource and data allocation in urban areas [13–15]. Digital data analysis facilitates the management of resource and information flows that are collected by a multitude of sensors; this allows for the application of efficient resource allocation schemes [16,17]. Two general domains of technologies can be observed. The first relates to digital participation, e-government, local sharing platforms, or solutions to public health issues, such as ambient assisted living solutions [18]. A second major domain of smart city concepts relates to aspects of sustainable development, most notably resource efficiency [5]. This includes water provision, waste management, material provision and use, and mobility, but most importantly energy production, distribution, and consumption. Due to the prominent role of energy technologies, smart city concepts foster the use of renewable energy production by means of solar panels, biomass, and wind [4,19]; such concepts are considered a serious technology pull for digitally monitored and allocated renewable energy production and distribution. Hence, resource efficiency is a central goal in smart city applications, while substitution and sufficiency aspects often play a minor role, demonstrating the technology-driven character of smart city strategies.

Yet the urban planning literature suggests that smart cities are not a panacea. Common critiques of smart city approaches in this field refer to issues such as data security, the ownership of data, the digital divide, or the influence of tech companies on urban politics [18,20]. In contrast, there is little discussion in the literature of the physical infrastructure of emerging smart city concepts, the need for critical raw materials (CRM), and related problems regarding the extraction, consumption, and subsequent removal of installed technologies as well as of CRM substitution and recovery. Despite many different indices and schemes, raw materials are typically assessed as critical once both supply risks and demand from key industries are high. Such assessments rely mostly on market macro-information and information from industrial players; in the past, they have predicted production problems in manufacturing industries due to CRM provision bottlenecks (e.g., [21–26]). Having the global growth of smart cities in mind makes the urgency of this issue clear from an urban planning perspective, even though it is currently impossible to make precise estimates of the potential CRM needs of smart city concepts.

Even though we are not able to precisely predict future emerging scenarios of smart cities, our motivation is to devote attention to the following issues. We wish to add the aspect of materiality to the current urban planning debate. Therefore, this descriptive and interdisciplinary commentary proceeds by combining urban planning literatures on smart city trends and literatures related to CRM mining, CRM substitution, and CRM recovery from scrap metals in order to highlight the resource problems that might emerge as part of the swift growth of smart cities. By so doing, we address the above presented issues by focusing on what we call the smart city-CRM-energy nexus. In the limited scope of this commentary, we exemplify this nexus via a case study of smart grids. Smart grids are essential in the smart city discussion and their production relies highly on CRM [17,27]. We therefore also refer to literatures on smart grids in Section 2, which focuses on the core function of energy production, energy distribution, and energy accumulation in smart grids. With a few exceptions, we selected the literature in this section based on whether the texts in question covered the functional element of smart grids and contained references to CRM. We acknowledge that the different elements of smart city approaches are closely intertwined and that smart grids are interdependently linked with the development of battery storage systems, especially the use of battery driven electric vehicles and vice versa [28]. Consequently, we also included literature on electric vehicles (EV) following the above criteria to exemplify the battery market leader, the lithium-ion battery. The literature in Section 3 was selected according to its coverage of CRM primary mining issues. By contrast, the literature in Section 4 focuses on the substitution and recovery of CRMs. This also covers ethical issues like health and the environment. Our intention in reflecting on this literature is to draw attention to not yet discussed issues in the future planning of smart cities. This will be the focus of the conclusion in Section 5.

2. The Smart City-CRM-Energy Nexus: The Case of Smart Grids

Smart grids for efficient resource and mobility flows demand high processing capacities and are intertwined with physical intelligent communication infrastructures [29–31]. In 2017, there were 950 European smart grid projects with a total budget of 4970 million euros [32]. Smart grids are expected to greatly boost intelligent communication technologies [27]. Here we outline the integral function of smart grids, including energy production, energy allocation, and energy accumulation (e.g., [29–31]):

- The renewable energy production sources with the most potential and efficiency are wind and solar panels, and they form part of many smart city energy supply scenarios [33–36]. The installed capacity of wind turbines rose from 17,400 GW in 2000 to 539,123 GW in 2015 [37]; turbines based on permanent magnets contain rare earth elements (REE) such as dysprosium, praseodymium, and neodymium. The production of solar panels globally advanced from 1 GW of installed cumulative capacity in 2000 to 229 GW in 2015 [38]. Solar panels classically rely on crystalline silicon and metalloid tellurium [32]. New solar panel applications rely on copper indium gallium diselenide/disulphide (CIGS) and cadmium-telluride [32,39]. Multi-junction cells or hybrid devices make use of nano-technologies, which rely on REE treatment of materials to produce more efficient solar cells [32].
- Energy allocation control devices, including processors built of semiconductors intended for steering purposes and for in-house applications such as smart meters as well as touch screens for visualization, are increasingly being used in smart cities [27,40]. They balance heterogenic electricity availability of renewable energy production technologies and connect through wireless sensor networks to enable real-time communication between the producer, distribution operator, and consumer, all linked via sensors with integrated processors [41]. The production of such devices relies on metalloids like gallium, indium, and silicon, but also on rare earth elements (REE) such as hafnium. Other sensor environments use optical fibers, which require the use of erbium [42].
- For energy accumulation (and electricity network stabilization), most smart city solutions such as e-mobility rely on lithium-ion battery storage devices, which are treated with REEs such as lanthanum and cerium [43–45]. CRMs such as silicon and graphite are needed for this type of battery construction [46]. Specifically, the dynamic growth of electric vehicles sales expected globally through 2030 [47] will provide new means of energy accumulation, which will jointly resolve smart cities' mobility and energy issues and result in increasing demand for cobalt [47,48]. This will increase the market domination of this type of battery, which already has an 85% share of the rechargeable battery market [49]. The electric vehicle battery addresses "transient duty cycles

typical of urban driving" [50] and is therefore especially suitable for use in smart cities, which aim for resource efficiency. Rising demand in the electric vehicle sector contributed to an annual 16% growth of the lithium-ion battery market [46], which is expected to grow to more than 92 billion USD in 2024 [51]. Nevertheless, even though battery electrical vehicle ranges are expected to rise, the costs of battery and electrical powertrains will need to decrease in order to put battery electric vehicles in an average price range [52].

Whereas the smart city literature recognizes the rising demand for "smart materials" [53] represented by CRMs like REEs [54], issues related to the progressively rising demand for raw materials due to the expansion of smart city concepts worldwide has not yet been discussed in the smart city literature. These issues pertain to the enthusiastic use of control, production, and storage devices, the back bones of smart cities, which will increase the demand for raw materials as summarized in Table 1.

Table 1. Energy in smart cities, exemplifying devices, and related CRMs.

Governance Domain	Exemplifying Device	Exemplifying Material
Energy allocation control	Semiconductor (cognition), mobility, (e.g., smart meter in-house)	REEs: Dysprosium, hafnium, neodymium, praseodymium, samarium, terbium
	LCD/PDP touch screen (visualization), mobility (e.g., smart meter, in-house)	REEs: Yttrium, cerium, europium, terbium Critical metalloids: Gallium, indium, tellurium
	Sensors with integrated processors, optical fiber (e.g., outdoor, in-house)	REEs: Erbium, hafnium, neodymium Critical metalloids: Silicon
Renewable energy production	Wind energy: Permanent magnet	REEs: Neodymium, praseodymium, dysprosium
	Solar: Photovoltaic panel	Critical metalloids: Gallium, indium, silicon, tellurium
Energy accumulation	Electricity storage, rechargeable lithium-ion batteries (e.g., electric vehicles)	REEs: Lanthanum, cerium Critical metalloids: Silicon metal, graphite, cobalt

Sources: [17,36,40,46,49,55–58].

3. Primary CRM Extraction for Smart City Energy Technologies

Studies on CRM extraction have underscored supply bottlenecks and therefore regard CRMs as critical resources on which high-tech industries like intelligent communication technologies (ICT) depend [21,59]. This also holds true for clean technologies such as smart grids and energy storage [32,60]. China's 2010 export embargo, as an outcome of its "Rare Earth Industry Development Plan (2009–2015)" [61,62], triggered skyrocketing REE prices [59,62]. This REE supply bottleneck, due to globally limited REE deposit diversification, has caused high dependence on Chinese REE mining, and, in combination with China's resource policy, it has prompted market insecurities; however, in 2011 China accounted for 95% of the global REE production [63]. In addition, metalloids, crucial for photovoltaics, face supply challenges [32,64]. The critical metals for photovoltaics are usually byproducts of other extracted industrial materials [65], for instance, indium, which is a byproduct of zinc mining [26]. The same holds true for tellurium [66] or gallium [67]. Industrial CRM policy strategies therefore aim at substitution and avoidance. However, considering REEs, they "are years away from militating against shortages" [68]. This is because of trade-offs, which manifest in the high costs of substitution [69].

There are also ethical considerations. The case of REE mining is a troubling one in this regard. Primary REE mining is associated with serious environmental threats, contaminating the air [70], soil, and water [71,72]. Uranium and thorium are associated with REE mining waste [73], and alpha particle emissions are therefore a major concern for REE mining [70]. This also applies to the processing of REEs, which produces radioactive, cancer-causing radon and monazite gases as well as alpha and gamma rays [74]. The environmental consequences of REE primary mining thus pose threats to human health. As Rim et al. stated, even though "wet gravity separation, dry high magnetic and electrostatic physical separation methods" are used during processing, "the main risks are the tailings, which are a mixture of small-size particles, waste water, and flotation chemicals, and arise at the concentration of the mined ore," which may result in lung diseases [75]. Studies conducted in communities in REE mining areas further indicate "monocyte depression across populations of children exposed to bone-seeking radionuclides." [61,76]

4. CRM Recovery: The Smart City as an Anthropogenic Scrap Metal Deposit

Despite the dominance of primary CRM mining, policy makers have opted for recycling of CRMs from scrap metals and mining heaps to reduce criticality (e.g., [22,77,78]). This is linked to potentially "reduced energy consumption, waste, pollution, and costs" [79]. During the last few decades, a discussion on so-called urban mining has emerged based on the idea that scrap metals can act as potential anthropogenic CRM deposits [57]. As far as potential urban CRM deposits are concerned, the life cycles pertain on the production side to products such as windmills and solar panels and on the consumption side to energy storage devices, liquid crystal displays (LCD) or plasma display panel (PDP) screens, smart meters, or semi-conductors. Whereas waste management has been discussed as a general topic in smart cities [80], little consideration has been given to the scenario of emerging smart cities and therefore to a potentially growing CRM-based technology demand as an emerging recycling issue.

From the lab perspective, the recovery of CRMs from scrap metals seems to be a feasible option, and high REE recovery rates can be expected from permanent neodymium magnets [81], semiconductors [82,83], as well as LCD or PDP screens [84,85]. REE recycling from scrap metals could potentially relieve criticality [25], but only around 1% of REEs are currently recovered from anthropogenic deposits [58]. However, the recovery of critical metalloids from waste solar panels seems rather problematic [86]. New photovoltaic materials, such as CIGS, are considered toxic [87,88] and are related especially to pulmonary and reproductive toxicity [89,90]. The recovery of tellurium [86,91–93]—as well as of lanthanum from nickel metal hybrid batteries [94–96] and lithium-ion batteries [97]—seems practically feasible. However, there are unresolved costs, there are energy and efficiency issues in relation to lithium-ion batteries [98], and there is generally low collection performance due to the lack infrastructures and agency [99]. Nevertheless, the recycling of lithium-ion batteries still remains an issue in regard to energy, cost efficiency, and safety [98].

There also remain knowledge gaps regarding the ecological and health aspects of recycling scrap metals [100]. Studies have indicated that contact with small REE particles might result in serious health issues [101]. For instance, erbium, which is used in integrated processor units in sensors [41], is considered toxic [75]. Bearing in mind that smart grids and other smart city applications will rely on sensors to a large degree and that small parts like central processing units are hard to recycle [102], the recycling of sensors might represent a future problem depending on the rate of their emergence. These recovery problems have to be taken into consideration when designing CRM recovery strategies, but they remain unaddressed in both the smart city literature and in smart city planning.

Again, the best solution to the problems associated with primary CRM mining and CRM recovery would be to substitute CRM with other less problematic materials. This would avoid market volatility and ethical issues. Yet, even though widely discussed, it seems that substitution is not a feasible solution and is only partially being realized, which is what the literature suggests [57,68,69,103,104].

5. Conclusion: Smart is Not Smart Enough!

We find three major challenges concerning the smart city-CRM-energy nexus: First, well-known problems related to its primary and secondary extraction or substitution will continue to get worse, to a degree that is yet unclear. Second, it is unknown whether existing policy-driven strategies, such as CRM deposit diversification, CRM recycling, or even substitution, will be enough to cater to the growing demand for CRM for the technologies needed for a global smart city scenario. Third, it is largely unclear what this local concentration of resource flows into anthropogenic CRM deposits—as represented by smart cities—will actually mean for the environment and human health but also for city governance. We argue that those three challenges should be urgently anticipated by smart city approaches, both in planning and governance, but also in the academic discussion. Thus, research on smart cities should deal with the downsides of the specific materiality of smart city concepts, based on innovative research perspectives such as global urban science [2] or geo-anthropology [105].

The smart city approach builds on emerging digital technologies, which, when embedded in city infrastructures, cause path dependencies and remain volatile to CRM price shocks. [54]. If secondary CRM extraction or CRM substitution are not options, one way to address this would be for technology producers and city governments to take a more active and responsible role in CRM primary mining governance and to manage their own scrap metal stocks. Currently, big groups, especially from ICT, dominate the smart city scene. By including those groups in city governance, urban areas are coming under direct control of corporate structures. This might reduce city authorities' capacity to cope with future unprecedented shocks. Therefore, governments should become aware that smart cities will become considerable consumers of CRMs and should demand more recovery and/or substitution solutions from the industries using these technologies. Future smart cities should anticipate the recycling and substitution capacities needed for such technologies so that they can deal with the huge amounts of toxic but valuable waste. This includes the recovery of materials from the anthropogenic deposits discussed here; however, life cycle assessment concepts for smart city infrastructures have yet to be developed. In the end, recycling the city will be a major issue and a costly downside of smart city planning.

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Abbreviations

CIGS	Copper Indium Gallium Diselenide/Disulphide
CRM	Critical Raw Materials
ICT	Intelligent Communication Technologies
LCD	Liquid Crystal Display
PDP	Plasma Display Panel
REE	Rare Earth Elements

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