clean hydropower generation while sustaining ecosystems, minimizing harmful impacts and balancing multiple water needs is an integral component. One particularly harmful effect not managed explicitly by hydropower operations is thermal destabilization of downstream waters. To demonstrate that the thermal destabilization by hydropower dams can be managed while maximizing energy production, we modelled thermal change in downstream waters as a function of decision variables for hydropower operation (reservoir level, powered/spillway release, storage), forecast reservoir inflow and air temperature for a dam site with in situ thermal measurements. For data-limited regions, remote sensing-based temperature estimation algorithm was established using thermal infrared band of Landsat ETM+ over multiple dams. The model for water temperature change was used to impose additional constraints of tolerable downstream cooling or warming (1–6 °C of change) on multi-objective optimization to maximize hydropower. A reservoir release policy adaptive to thermally optimum levels for aquatic species was derived. The novel concept was implemented for Detroit dam in Oregon (USA). Resulting benefits to hydropower generation strongly correlated with allowable flexibility in temperature constraints. Wet years were able to satisfy stringent temperature constraints and produce substantial hydropower benefits, while dry years, in contrast, were challenging to adhere to the upstream thermal regime.

Keywords: Hydropower, Ecosystem-safe, Temperature change, Remote sensing, Optimization, Regression

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Introduction

The need to satisfy energy demand of a growing planet while simultaneously meeting sustainability standards with clean energy generation has resulted in a growing hydropower infrastructure, especially in the developing regions (Moran et al. 2018). The design and management of such infrastructure has traditionally focused on flood control, hydropower, water supply, and irrigation (Carron and Rajaram 2001). Hydropower, once perceived as clean and renewable, has now become a contributor of negative ecological impacts to the reservoir and aquatic and riparian ecosystem (Abbasi and Abbasi 2000). Hereafter ‘reservoir’ and ‘dam’ are used interchangeably to imply the reservoir-dam system.

Coldwater fishes such as salmon and trout are sensitive to changes in water temperature. Extreme temperature deviations can be lethal to their population (Handcock et al. 2012). Warm water tends to hold less dissolved oxygen which is critical to the health of aquatic habitat (Li et al. 2014). Such adverse thermal impacts of hydropower dam operation demand a reevaluation of dams’ operational objectives from an ecosystem standpoint (U.S. Department of the Interior 1995; McCartney 2009). In the past, recommendations have usually specified minimum flow release from reservoirs for habitat maintenance, water quality, and temperature control (Carron and Rajaram 2001; Chen and Olden 2017). However, little or no recommendation exists in the form of operational strategy to minimize the negative ecosystem impacts from a thermal standpoint. Thus, one of the formidable challenges that exist today and will only intensify in the future with changing climate and increasing hydropower dam construction (Moran et al. 2018;

Zarfl et al. 2015) is the alteration of river's natural thermal regime by the hydropower operations (Olden and Naiman 2010).

Thermal pollution from hydropower operations

The natural temperature of regulated rivers, apart from responding to changes in hydrologic and hydraulic conditions, is largely impacted by the operations of regulating reservoirs in the upstream (Gu et al. 1999). During the seasons of maximum heat exchange between reservoir surface and atmosphere, the surface warms rapidly lowering its density. The lower density surface rests on top of water column that becomes colder and denser with depth. This inhibits the vertical mixing of reservoir and causes seasonal thermal stratification with low diffusion rates between the top and bottom reservoir layers, also termed as epilimnion and hypolimnion, respectively (Niemeyer et al. 2018; Xie et al. 2017). The surface warming is also enhanced by the large reservoir surface area and resulting longer residence time of the rivers (Vörösmarty et al. 1997). During hydropower operations, penstocks, usually located at the bottom layers (hypolimnion), tend to release cold water and lower the downstream peak temperature (Carpentier et al. 2017). In late summer and autumn, the stratification breaks as the reservoirs are drawn down through the spillway to provide flood storage capacity for the coming winter and spring precipitation. This leads to a well-mixed reservoir with downstream temperatures warmer than the natural regime. Such alterations in temperature regime, also termed as thermal pollution create challenging conditions for spawning and rearing of certain fish species and can be lethal for aquatic life (Olden and Naiman 2010).

The persistent thermal pollution from hydropower infrastructure worldwide, if left unaddressed, can potentially dwarf the benefits harnessed for renewable energy. According to the prediction from US Energy Information Administration, world's energy demands will grow up by 50% from 2018 to 2050, mostly driven by steep rise in developing nations (U.S. Energy Information Administration 2019). This is proportionally increasing the installation of newer hydropower capacity in these countries. One of the striking examples is that of Laos which is aiming to become the "battery of Southeast Asia" by investing heavily in the hydropower dams across the nation (Rujivanarom 2019). While such a rise of new hydropower dams in emerging economies is inevitable, the only way to sustain the ecosystem while still generate clean energy is to improve their operational efficiency in terms of minimal impacts to the ecosystem.

Need to improve hydropower efficiency

In contrast to developing nations, developed nations have saturated their dam installation capacity (Labadie 2004). As the escalating environmental impacts are being identified, the efforts have started shifting towards mitigation. The Federal Energy Regulatory Commission (FERC) in United States examines the environmental impacts and issues operational changes through 30- to 50-year licenses (Bednarek 2001). There have also been efforts to undam the rivers when the mitigation tolls are not enough. More than 1200 dams have been removed in the United States, especially in the past two decades (Bellmore et al. 2017). While dam removal has become commonplace to deal with aging and uneconomical dams, the resulting loss of reservoir habitat and movement of sediments can incur heavy costs to the ecology and environment (Stanley and Doyle 2003). Given the increasing need for clean and stable supply of baseload (Matek and Gawell 2015), removing the infrastructure would also be unfavorable for sustainable energy goals. From a logistical standpoint, the time and accrued cost of each dam removal would demand immense resources and a few centuries to remove all the dams the right way. As dams have become pervasive features of the river systems, continued improvement in the efficiency of dam operations is therefore the more pragmatic approach to maximize their benefits to humans and ecosystem.

Despite the recognized impact of dams on river's thermal regime (Olden and Naiman 2010; Gu et al. 1999; Niemeyer et al. 2018; Rheinheimer et al. 2014), the quantitative effect of hydropower operations on downstream water temperature and the subsequent consequences on ecosystem have received little attention (Bonnema et al. submitted). Mitigation efforts to reduce thermal pollution from hydropower dams either focus on structural measures such as construction of selective withdrawal structures (Rheinheimer et al. 2014) or, by specifying required instream or minimum spillway flow downstream of the reservoir (Tharme 2003) based on an environmental flow assessment (King et al. 1999). The selective withdrawal outlets require additional construction and can be unviable for a reservoir due to the involved logistics and monetary constraints. Relying on environmental flows for controlling the downstream temperatures is prone to result in suboptimal conditions for the aquatic habitat particularly in conditions when inflow regime deviates from the climatology. Instead, a more dynamic scheme that considers inflow forecast information at short-term weather scale can guide the dam operator ahead of time on optimal operations for realizing ecologically safer downstream conditions (Ahmad and Hossain 2020).

Optimization of reservoir operations has been extensively studied for various operating objectives at short- and long-term operation scales (Labadie 2004; Yeh and Becker 1982; Barros et al. 2003; Ahmad et al. 2014). Multi-objective optimization for hydropower has been performed to satisfy other stakeholder benefits of flood control, water supply, irrigation and water quality (Le Ngo et al. 2007; Yazicigil et al. 1983; Shaw et al. 2017; Asadieh and Afshar 2019). Ahmad and Hossain (2020) optimized daily operations of two dams in US to maximize hydropower without compromising flood control. Jordan et al. (2012) presented optimization of turbine and bottom outlet operations for flood protection in a hydropower multi-reservoir system in Switzerland. Similar to flood control, maintaining a stable thermal regime also competes against the energy maximization objective as higher release or storage can significantly change downstream temperature. However, the inclusion of downstream river temperature as a constraint has not yet been explored or reported in published literature to the best of our knowledge.

Need to model reservoir temperature

Incorporating water temperature as a constraint within an optimization scheme for hydropower generation requires quantitative relationship between the reservoir operations and changes in downstream thermal regime. There have been efforts to model the river temperature using deterministic and statistical models. Deterministic models, based on governing equations for heat transport, flow, and climatic conditions, do not explicitly include the reservoir operations as parameters for modeling temperature (Benyahya et al. 2007). Also, they typically require intensive hydrological and meteorological data input and computational effort in model building and calibration. Distributed river temperature models also exist that simulate river network by discretizing the river cell (Li et al. 2015; Yearsley 2012). Some of them often explicitly simulate reservoir's thermal stratification by integrating land surface models (LSMs) with hydrodynamic models (Niemeyer et al. 2018; Buccola et al. 2016). Even complex three-dimensional models have been used such as by Jiang et al. (2018) to study thermal pollution in Lancang River using Delft3D-FLOW model. However, a major limitation with these complex models is the inability to integrate them with the hydropower optimization framework.

Another challenge towards temperature-constrained optimization is the dearth of in situ temperature measurements. The water temperatures in rivers are limited by sparse sampling in both space and time (Handcock et al. 2012). The scarcity of in situ temperature measurements is even more prominent in the developing nations that present major hurdles in building and validating the temperature models. Recent advancements in thermal infrared (TIR) remote sensing can quantify spatial and temporal patterns of surface water temperature at multiple spatial scales (Ling et al. 2017). This has been demonstrated by Bonnema et al. (submitted) where dry season water temperature cooling trends correlated with dam development in the Mekong basin, analyzed using 30 years of Landsat TIR observations. Thus, applications for ecologically sensitive hydropower optimization are better served by simpler river temperature model that can relate downstream temperature against decision variables for dam operations and global-scale satellite-derived temperature (where in situ data is scarce).

Only a few studies have explored simple regression models for stream temperature changes. Neumann et al. (2003) presented empirical model for daily maximum stream temperature in summers using average daily flow and air temperature as predictors. Mohseni et al. (1998) predicted weekly temperatures for fish habitat evaluation using nonlinear function of weekly air temperatures. The heat storage effects were considered by developing separate models for warming and cooling season. Benyahya et al. (2007) reviewed different regression models used for stream temperature. However, inclusion of reservoir operations in the regression model at daily time step has not yet been investigated in the literature. Because ecological impacts are more sensitive to changes in downstream temperature from natural thermal regime and not their absolute values, regression model offers an attractive alternative for the purpose.

The pertinent issues with the current state of hydropower operations, brief summary of the existing literature and proposed solutions.Datasets—observed and forecast
To understand how the downstream temperature changes as a function of hydropower operations, in situ measured temperatures were obtained from U.S. Geological Survey (USGS) stations located on both the upstream tributaries and downstream river channel (Fig. 2). Flow-averaged temperatures were obtained from USGS stations on three rivers upstream of Detroit reservoir (44° 43′ N, 122° 15′ W). The downstream temperature station is located below the Big Cliff dam and accounts for regulation effects from both the dams. The upstream stations

measure temperature of the top surface or epilimnion of the reservoir while the downstream stations represent average temperature of the downstream water column due to reduced tailwater stratification. The forecast meteorological fields were acquired from the NWP model of Global Forecast System (GFS) for forecasting reservoir inflow. The GFS fields were acquired at 0.5° resolution for 1–7 days lead-time with a 3-hourly temporal resolution. Air temperature was obtained from CPC Global Temperature data provided by the NOAA/OAR/ESRL PSD, Boulder (https://www.esrl.noaa.gov/psd/). The observed reservoir inflow and operations data were obtained from USACE (2019).

Datasets—remote sensing

The primary data source for remote sensing-based water temperature estimation was a series of Landsat-7 ETM+ (Tier 1) satellite images. The TIR band (10.45 to 12.5 μm) is acquired at a resolution of 60 m. The image processing and temperature estimation analysis was performed in the cloud computing environment provided by Google Earth Engine (Gorelick et al. 2016).

As the river channel downstream of Detroit dam is quite narrow, the pixels in TIR band acquired over water at 60 m possibly represent mixed pixels with a portion of reflectance contributed by surrounding land cover. Thus, ten dam sites with varying reservoir depths and downstream river width were chosen to explore the effect of pure water pixels in temperature extraction. The locations of selected dams and their average reservoir depths are shown in Fig. 4. Additional file 1: Table S1 summarizes the selected dams, their coordinates, approximate downstream river channel widths, respective Landsat-7 ETM+ scene path and row numbers, and USGS stations for upstream and downstream in situ temperature measurements.Hydropower has been the leading source of renewable energy across the world, accounting for up to 71% of this supply as of 2016. This capacity was built up in North America and Europe between 1920 and 1970 when thousands of dams were built. Big dams stopped being built in developed nations, because the best sites for dams were already developed and environmental and social concerns made the costs unacceptable. Nowadays, more dams are being removed in North America and Europe than are being built. The hydropower industry moved to building dams in the developing world and since the 1970s, began to build even larger hydropower dams along the Mekong River Basin, the Amazon River Basin, and the Congo River Basin. The same problems are being repeated: disrupting river ecology, deforestation, losing aquatic and terrestrial biodiversity, releasing substantial greenhouse gases, displacing thousands of people, and altering people's livelihoods plus affecting the food systems, water quality, and agriculture near them. This paper studies the proliferation of large dams in developing countries and the importance of incorporating climate change into considerations of whether to build a dam along with some of the governance and compensation challenges. We also examine the overestimation of benefits and underestimation of costs along with changes that are needed to address the legitimate social and environmental concerns of people living in areas where dams are planned. Finally, we propose innovative solutions that can move hydropower toward sustainable practices together with solar, wind, and other renewable sources.

We need innovative sustainable solutions to meet energy demands, guarantee food security, and ensure water availability around the globe. Over the years, dams have been used for land management and flood control; to store water for irrigation and agriculture; to provide recreation and navigation, and to address management of aquatic resources (1, 2). There are over 82,000 large dams in the United States alone (3, 4). In addition, over 2 million small low-head dams fragment US rivers (5), and their cumulative impacts are largely unknown, since they have escaped careful environmental assessment.

Beginning in the late 19th century, the first hydroturbines were invented to power a theater in Grand Rapids, Michigan and then, to power streetlights in Niagara Falls, New York. Alternating current then made possible the first hydropower plant at Redlands Power Plant, California in 1893. Beginning in the 1920s, the US Army Core of Engineers began to build hydropower plants. The Tennessee Valley Authority in 1933 developed hydropower in the Tennessee River with the clearly stated goal of promoting rural electrification, later widely imitated throughout the country—the most notable being the Hoover Dam in 1937. The New Deal gave an enormous boost to hydropower construction, tripling output in 20 years until it accounted for 40% of electrical use in the United States (6). Hydropower dams were an important part of North American and European energy development.

Starting in the late 1960s, big dams stopped being built in developed nations, because the best sites for dams were already developed, the costs became too high, and most importantly, growing environmental and social concerns made the costs unacceptable. Since then, the contribution of hydropower to the United States' electrical supply has steadily declined to 6.1% of energy consumption, and other energy sources, such as nuclear, gas, coal, solar, and wind, began to replace it. Dam removal rather than construction has become the norm in North America and Europe, because many that were built before 1950 are at the end of their useful lives, they would be too costly to repair, many no longer serve their initial purpose, and their social and environmental negative externalities became unacceptable (7). European countries with favorable topography and rain patterns, such as France and Switzerland, continue to have hydropower as an important part of their energy mix through technological innovations at existing dams. In contrast, 3,450 dams have been removed to date in Sweden, Spain, Portugal, the United Kingdom, Switzerland, and France (https://www.damremoval.eu). Hundreds of dams were removed in the United States (546 from 2006 to 2014) (7) and Europe at enormous financial cost. This situation contrasts with what is happening in developing countries.

Developing countries, where millions of people are still not connected to the electric grid (8), have been ramping up hydroelectric dam construction for decades. These often involve megaprojects, which repeat the problems identified with big dams built in the past by the United States and European nations: disrupting river ecology, causing substantial deforestation, generating loss of aquatic and terrestrial biodiversity, releasing large amounts of greenhouse gases, displacing thousands of people, and affecting the food systems, water quality, and agriculture near them (9–12). The sustainability of these undertakings is commonly insufficiently scrutinized by those promoting them. The priority in large dam construction is to generate energy to serve growing industries and urban populations—these two things often overwhelm socioeconomic and environmental considerations (13). Left behind are local communities saddled with socioenvironmental damages and loss of livelihoods (14). Often, they do not even gain access to electricity, because they are not provided the power from the large dams, and they are not sufficiently compensated for their disrupted lives. All countries need renewable energy, and hydropower should be part of this portfolio. However, there is a need to find sustainable and innovative solutions that combine hydropower development with other energy sources, thus providing benefits that will outweigh, reduce, or even eliminate the negative environmental, behavioral, cultural, and socioeconomic externalities resulting from large dams.

Here, we review the socioeconomic and environmental situation in several major river basins where dams are being built. We examine the proliferation of large dams in developing countries, the lack of attention to climate change in the decision of whether to build a dam, some of the governance and compensation challenges, and the overestimation of benefits and underestimation of costs. We also identify changes that are needed to address the legitimate social and environmental concerns of people living in areas where dams are planned and propose innovative solutions to meet the food, water, and energy needs of citizens in those regions. These solutions have relevance worldwide, as hydropower can also contribute to meeting goals of reducing fossil fuel emissions and building sustainable communities with diversified energy sources.

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HYDROPOWER IN DEVELOPING COUNTRIES

An estimated 3,700 dams that produce more than 1 MW are either planned or under construction primarily in developing countries (15). It is easy to understand why: hydropower represents the largest renewable source of electricity (71% of global production of renewable energy) (16), and it is estimated that only 22% of the global potential is exploited to date (15). Substantially increasing the share of renewable energy in the global energy mix by 2030 is among the Sustainable Development Goals. Hydropower development is a global phenomenon and multinational in its significance. It is affecting the most important river basins in the world, including the Amazon, the Congo, and the Mekong (12, 17), creating enormous disruption in these ecologically important regions. The financial costs of the dams are immense, and many believe that the benefits do not outweigh the costs (18, 19). The hydrologic consequences of large-scale dams and reservoirs are extensive (20); however, microhydropower is largely a net positive for communities and has minimal environmental impact (21, 22). Sharp declines in available freshwater due to dam construction drive seasonal changes in river discharge as well as loss of downstream freshwater habitat, floodplains, and even coastal erosion and salinity changes (23–26). The negative consequences for ecosystem structure and composition (e.g., habitat fragmentation, loss of aquatic and terrestrial biodiversity) and function (e.g., nutrient flows, primary production) can be severe (7, 18, 19). Reservoirs can also be significant sources of greenhouse gases, especially methane (10, 23, 27–30), and reductions in river flow can increase pollutant concentrations (31, 32).

The human costs of large dams are no less important. The social, behavioral, cultural, economic, and political disruption that populations near dams face are routinely underestimated (19, 33, 34). Ansar et al. (18) in a global analysis of 245 large dams built between 1934 and 2007 found that costs of large dams were 96% higher than predicted costs and that 1 out of 10 large dams cost up to three times more than originally estimated. For fishermen relying on fishing resources for their subsistence, the changes in the ecological system brought by big dams alter their livelihoods in negative ways (35, 36). A report of the World Commission on Dams (WCD) (37) documented the socioeconomic problems due to dam development projects; 40–80 million people were displaced, and it has proven challenging to resettle them properly. Scudder (38) estimates that 80 million people were displaced in the last century because of dams. In addition, the living conditions and food security of communities living downstream are often placed in peril. In the Tucuruí Dam region of the Brazilian Amazon, the fish catch declined by 60% almost immediately, and more than 100,000 people living downstream were affected by the loss of fisheries, flood recession agriculture, and other natural resources (37). A conservative estimate is that 472 million people worldwide have been negatively affected by dam construction downstream from dams (39). However, the impact on downstream communities is still understudied (40). Large dams seem to be everything that one should not try to build if one cares about sustainability. To move toward sustainability, future hydropower development needs to give more attention to how climate change may affect hydropower production and make greater efforts to reduce the environmental and social costs borne by people near the dams. In addition, those harmed by the dams need to be adequately compensated, the number of people that must be resettled should be reduced, and most importantly, innovative technologies that reduce all of these negative outcomes should be developed, especially instream turbines and other forms of renewable energy.

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DAMS, CLIMATE CHANGE, AND LAND USE CHANGE

Hydropower development in developing countries seems to overlook climate change scenarios. In developed countries, some dams (e.g., Hoover Dam) are already putting new turbines at a lower elevation to prepare for projected future water shortages in the Colorado River due to climate change. Lake Mead, which stores the water for the Hoover Dam, has seen a 40% decline in its water level (41); despite technology improvements, its peak power output is down from 2 to 1.5 GW. Improvements have also been successfully undertaken in the Southeast United States in several dams through the relicensing process that mandates improvements in river flows, facilitating fish migrations and enhancing dissolved oxygen levels in water discharges to maintain river ecology (42). According to a recent US Energy Information Administration Outlook, the vast majority of the world’s newly installed renewable energy over the next 25 years will come from hydroelectric dams, mostly in the developing world. Here, climate change impacts are already felt but again, are not being addressed by dam builders. Projections for the Amazon Basin point toward a broad drying trend in the southern and eastern regions (ref. 43, figure 27–2), especially under higher-greenhouse gas emissions scenarios. Variability (particularly in droughts) has also been increasing for these regions (43, 44); this is projected to continue and will diminish reliable water supplies to dams. The Jirau Dam and

Santo Antonio Dam on the Madeira River in the Brazilian Amazon, completed only 5 years ago, are predicted to produce only a fraction of the 3 GW each that they were projected to produce because of climate change and the small storage capacity of run-of-the-river reservoirs. The Belo Monte Dam on the Xingu River, completed in 2016, will also produce less due to climate variability and a relatively small reservoir: only 4.46 of the 11.23 GW that it was built to generate even in optimistic scenarios in 10 of 12 mo of the year due to insufficient water levels (43, 45). Since 2005, the Amazon has experienced three droughts that broke all historical records (and 3 extreme flooding years) (46, 47). Most climate models predict higher temperatures and lower rainfall in the Xingu Basin, the Tapajos Basin, and the Madeira Basin (43, 44). The intensity and frequency of extreme events continue to challenge the energy promises from investments in large hydropower projects.

Hydropower is the world's primary renewable energy resource, but questions have been raised about its reliability under projected climate change. In Brazil, which depends on hydropower for up to 67% of its electrical energy (48), this is a crisis waiting to happen. However, the response to likely reduced capacity from climate change has been to accelerate dam construction in these subbasins, even when this has meant not following international laws of free and open consultation with local and indigenous people (49), rather than investing in technologies with lesser environmental impact, such as instream turbines (50, 51), and investing in other sources of renewable energy, like solar, biomass, and wind, to diversify the energy mix (45, 52). More concerning is the plan that most future hydropower in South America will come from the river-rich Amazon Basin, where there will likely be serious environmental and social consequences (36). The same can be said for Asia, where the Mekong is currently being dammed at an accelerating pace (53, 54). These basins contain 18% of global freshwater fish diversity (17); therefore, the construction of dams in these basins poses a threat to fish biodiversity and imperils the food security of the region's inhabitants.

In a similar manner to climate change, dam builders frequently fail to consider the effects of land use change on the hydropower potential of a dam. Stickler et al. (14) examined the loss of energy generation potential under deforestation scenarios in the Amazon River Basin. In the Xingu Basin, site of the Belo Monte Dam, they estimate that ~38% of the industry's power estimates could be reduced due to predicted deforestation and that power generated could fall below one-half of installed capacity in all but 2 months of the year (14). Regional deforestation can inhibit rainfall and soil moisture sufficiently in tropical moist forest regions to constrain energy generation (55). One-half of precipitation in the Amazon Basin is estimated to be due to internal moisture recycling; thus, deforestation can reduce precipitation independent of the expected decline from global climate change (56). Reliance on large dams for generating hydropower can be questioned as a reliable strategy under climate change scenarios. Alternatives that can address the energy production shortfall in drought years need to be considered. A recent assessment found that the best scenarios include rapid development of wind, biomass, and solar to complement the existing installed hydropower. The latter is not expected to meet the demands of the future, which will be more reliably provided by a complement from solar, biomass, and wind power generation, with existing hydropower providing stability to the grid (52).

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DAM FAILURES AND DAM REMOVAL

It is easy to forget, as one seeks “green energy” technologies, that dams have a finite lifespan (i.e., that they are not really a sustainable long-term strategy). Dams being built in Brazil are planned for a 30-year lifespan, which could be extended with technical retrofits and newer turbines (45). Two sources of dam failure are the aging of the construction materials and accumulation of sediment behind the dam impoundment. As dams age, they are prone to failure, sometimes resulting in numerous fatalities and great loss of property. Heavy rains from a single tropical storm in 1994 caused more than 230 dams to fail in Georgia (57). The Oroville Dam Spillway began to fail in California in 2016 after heavy rains, resulting in the evacuation of 190,000 people from their homes. More famously, the Teton Dam in Idaho failed in 1976, with resulting losses exceeding $2 billion in 2017 dollars. Many US dams have significant potential for failure. Many built during the peak construction period in the United States (1930–1950) are past their 50-year lifespan, with 85% of them reaching that milestone by 2020 (58).

The cost of repairing a small dam can be up to three times the cost of removing it (59), which is an important reason for the growing trend to remove dams today. If the costs of dam removal were considered in a dam’s costs, would their construction be justified? More than 60 dams per year are being removed in the United States, a trend that began in 2006. Varying by the amount of sediment load on the river, sedimentation problems occur faster than loss of structural integrity (60). Before 1960, sedimentation rates were not consistently factored into dam design criteria; thus, many dams are expected to fill at rates exceeding design expectations (61, 62). Today, engineers typically design reservoirs to incorporate a 100-year sediment storage pool. However, these calculations often fail to include changes in watershed land use (such as road construction, which can increase sediment yield by two orders of magnitude) and projected extreme events due to climate change that will likely increase sediment transport toward reservoirs. This tendency to overlook factors that could increase sediment loads continues today in tropical countries. For example, the Madeira River carries 430 Mt of sediment per year (63), which is orders of magnitude greater sediment than most rivers. Two dams were completed during this decade on the Madeira—Jirau and Santo Antonio—and additional ones are planned, despite numerous warnings that their designs have underestimated the high sedimentation rates (64–66). In less than 5 years since their completion, experienced dredgers who earlier mined for gold in the Madeira (and who had been removed from the area to build the dam) have had to be called back to remove sediment accumulating in these two reservoirs at “unexpected” rates according to the dam builders. This is an unjustified surprise given the number of scientific papers that had warned about the likelihood of such rapid sedimentation

ROLE OF GOVERNANCE IN HYDROPOWER’S SUSTAINABILITY

Whether in the Amazon, the Congo, or the Mekong, the most overlooked dimension of hydropower projects is the effects on local social systems and institutions (84, 86, 87). Local communities typically do not have a significant say in hydropower development (88, 89). This results in a decoupling of decision making that can result in local priorities being overlooked and the interests of urban industrial sectors driving decisions. In addition, policies and regulations are often regional or national and commonly do not recognize the transboundary system dynamics, thus neglecting important considerations, such as rights, social and cultural values, and access to resources (90, 91). Institutions can be specific to each sector (e.g., water allocation regulations, property rights, renewable energy policy tools) as well as apply across sectors (e.g., political and civil rights, decentralization policies). Similarly, institutions can operate at different scales of governance (i.e., local rules and norms, state regulations, national laws) and shape how groups make food, water, and energy choices. However, one needs to start thinking about the governance not as three different sectors but as a nexus, in which multiple layers account for the different scales, levels, and sectors (90). Institutional analyses of case studies become necessary to create an integrated policy assessment of the cases under consideration. For example, energy production through water appropriation highlights local–regional–national–transnational tradeoffs, in which water, energy, food, and livelihood costs and benefits are inequitably treated.

Often, large dams are promoted with the idea that locals will gain some benefits out of them. However, the evidence suggests otherwise. A recent study using a database of 220 dam-related conflicts found that, in dams surrounded by controversies and conflict, the use of repression, criminalization, violent targeting of activists, and assassinations was common (92). This is a result of a failure of the hydropower sector to address governance and sustainability issues. Communities affected by dams have frequently complained about the lack of consultation and attention to known negative impacts on society and environment as well as the questionable promises made by the energy sector (cheaper energy bills, more jobs, better infrastructure, such as schools and hospitals). Benefit-sharing mechanisms, such as compensations, were proposed by the WCD report as a way to share the benefits of the dams with local communities (93, 94). In Brazil, municipalities are supposed to get some revenues from dams; however, these resources sometimes never arrive (95). In Belo Monte, Santo Antonio, and Jirau, which were installed on the Brazilian Amazon, the electric bills of people went up rather than down, and the jobs promised to locals went mostly to outsiders and disappeared within 5 years. Community organizers and indigenous leaders are the most frequent targets of violence and repression (36, 92, 96–98).

Millions of people worldwide are affected by dam construction either because they are permanently resettled due to the filling of the reservoirs or because their livelihoods get disrupted with the construction and operation of the dam (86). However, there do not seem to be mechanisms to fully compensate them for their losses (99). People who are displaced often get an undervalued price for their land or buildings that does not consider the social, cultural, and religious value of their land or the way that people make their livelihoods on the land or the stretch of river (96, 100, 102). In addition, it does not consider that, after resettlement, people often lose their social networks and other types of social wealth, which has economic, cultural, social, and health consequences (86, 99). Communities that are not displaced, like those that are downstream, generally do not get any compensation, although the effects of the dam on their livelihoods are just as great as the effects on those who require resettlement (39, 102). This problem seems to be even more significant considering that most people affected by the dam are the poorest and more vulnerable in their societies, and they are often indigenous and traditional communities (19). Monetary or nonmonetary compensation mechanisms should consider that men and women are impacted differently by a dam and ensure that the most vulnerable are compensated (102).

As one seeks to build a just and sustainable hydropower sector it is important to build mechanisms that guarantee that externalities will be internalized; in other words, those who benefit from hydropower and are far away (and thus do not face externalities from its exploitation) need to compensate local populations where hydropower is produced to offset the negative costs from energy production (13). They should also offset the heavy losses from transmitting power across great distances. A key function for institutions is reducing transaction costs that hinder the identification of such inequities and externalities as well as the functioning of offset programs.

Creating compensation mechanisms that are not always monetary is an important innovation needed for future energy development plans. To date, little attention has been given to compensation forms that strengthen communities and individuals affected by dams. This can be done by investing in understanding the social capital and history of these communities and working with them to sustain the integrity of their social, economic, and political relationships. The contrary has been more common: resettling people without concern for any of these issues and sometimes, even seeming to purposely break up any preexisting social organization as a way of preventing their ability to act after the dam is built to lobby for adequate compensation (103).

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INNOVATIVE SOLUTIONS FOR HYDROPOWER

Several things are needed to transform the hydropower sector to enable the benefits to exceed the costs and to ensure that dams contribute to sustainable energy systems. (i) Environmental impact assessments (EIAs) and social impact assessments (SIAs) need to be capable of stopping a dam from being built. (ii) EIAs and SIAs must be carried out by firms serving citizens rather than the dam builders, and they are essentials tools worldwide, whether in Brazil or Europe (104). (iii) Hydropower designs need to truly allow fish passage and mimic the seasonal river flows. (iv) Better governance needs to be created around dams. (v) Greater transparency with society about the true costs and benefits (including social, cultural, economic, political, and environmental costs and the costs of dam removal at the end of the dam lifespan) is needed. (vi) Sustainability evaluation measures from the design through operation stage should be used. (vii) Innovative technologies that do not require damming the river or resettling population are needed. Addressing these issues can transform the hydropower sector.

(i) EIAs and SIAs need to have real teeth. They should be carried out with sufficient lead time to provide a credible assessment and have built-in capacity to stop the building of a dam if needed protections to biodiversity and human populations are not in place (33). Public hearings and sufficient social engagement addressing the consequences from the dam have to be allowed before final approval is given. SIAs are fundamentally important to determine how many people will need to be resettled and lay out the mechanisms for appropriate indemnity and compensation. There also need to be mechanisms to ensure that these recommendations are carried out rather than leaving this up to the construction companies (33). Compliance with Article 169 of the International Labor Organization (105), requiring previous and free consultation with indigenous and traditional populations, should be expected as part of the predam planning in a manner that allows full discussion of the pros and cons without underestimating costs and inflating benefits to those affected.

(ii) EIAs and SIAs should not be carried out by the firms engaged in building the dam or their subsidiaries (as is currently common in some countries); these need to include biodiversity and social impact studies by independent organizations responding to civil society with no conflict of interest with the government, energy sectors, or construction companies. Actual practice suggests that EIAs and SIAs are commonly carried out by consulting firms hired by and responding to prospective dam builders, and their data and results are often not made publicly available to stakeholders until long after the dam is built. Benefits are routinely inflated, and costs are minimized in current EIAs and SIAs (33). When benefits are not forthcoming and costs are large, the population ends up in court seeking compensation for damages, and these costs are paid by society and not by the dam builders.

(iii) At present, most devices (“ladders”) to help migrating species get across dammed areas do not work or are not even put in place. Targets for fish passage are being missed by several orders of magnitude—even in the best of cases, only 3% make it (106); the authors make a case to admit the failure of these ladders and propose dam removal in cases where fish passages are not working. They propose a cautionary tale for developing countries’ current efforts, arguing that fish passages do not compensate for the damage to the fisheries, since they generally do not work. This needs to change, and attention must be given to greatly improved designs that avoid species extinctions and allow running fish to spawn rather than die trying. At Belo Monte, 16.2 tons of fish died, as they were unable to get past the dam during the 2016 migration (107). Prioritizing energy production at the expense of the fish biodiversity and abundance in the rivers must stop. Releases of water from a dam should mimic a river’s natural seasonal fluctuations to maintain stream health. Experiments in Sweden that mimic the natural stream flow were able to improve the quality of the downstream ecology with only small reductions in hydropower production (108).

(iv) Energy generation through dams requires thinking about the governance implications of the dam construction and associated energy distribution and use. Policy makers often see energy as the entry point to the system and use water as a way to generate it without recognizing the effects on food and livelihoods. The three sectors are dependent on each other, but policies are rarely conceived with a nexus approach, which has to change. The challenge is even larger when the food–water–energy nexus has implications that go beyond one country, either because the impacts are suffered by different countries or when multinationals or different states are involved in the construction or distribution of energy. The current construction of binational hydroelectric dams on the Bolivia/Brazil border is a clear example of this challenge. Flooding from Jirau has led to flooding in Bolivia (36).

(v) To overcome the limitations of current dam-building practices, one needs to incorporate how regional to national policies affect the local issues in the design of dams, and such information needs to be made available to the likely affected societies in a transparent manner. There is a lack of regional to multinational planning that considers the impacts of dams in a manner that ensures connectivity of the ecosystems (109, 110). The goal is to improve assessments to incorporate community concerns and to design new dams in ways that they can improve livelihoods by increasing crop productivity, maintain fisheries yields, increase food security, and improve access to water and energy from the project. Following WCD recommendations or a rigorous cost/benefit analysis would have resulted in Belo Monte not being built. The analysis showed that there was a 72% chance that the costs of Belo Monte would be greater than the benefits (111), something that has proven correct. By the guidelines set out by Scudder (86), an experienced scholar of dams and resettlement across the world, many or even most large dams should not have been built. Those guidelines and those of other bodies, such as the WCD, agree on much of what is wrong with the current rush to build large dams and the apparent difficulty in meeting those minimal guidelines.

New tools are being proposed by scholars that permit basin-wide policy instruments using existing laws. For example, the multinational Amazon Cooperation Treaty and Brazil’s National Water Law (112) promote integrated water management and could be tools to change how decisions are made. An international panel of experts could use existing knowledge to determine vulnerabilities using tools, such as the Dam Environmental Vulnerability Index (113), at the subbasin scale. These tools and engaged civil society and other stakeholders in a joint panel could more accurately consider the environmental and social costs. The energy sector in countries like Brazil and India has recently promoted and begun constructing small dams or PCHs as a more benign technology than large dams, yet there is very little evidence for this claim (45). The United States has a long history of building low-head or small dams (2 million of them); however, Fencl et al. (5) note that the claim of their minimal impact is largely untested. By virtue of their abundance, small dams can substantially impact flowing aquatic ecosystems (114). Small hydrodams possess the same characteristics as large dams, with the only difference being their size. China and India are the current leaders in small hydrodams. Their power generation benefits, particularly in isolated mountainous terrain, cannot be dismissed. However, their ecological, hydrological, and social impacts should be scrutinized just like large dams, and more importantly, they are losing ground to wind power in energy auctions (i.e., their cost per kilowatt is no longer competitive compared with wind power generation). Small hydropower is subject to both environmental impact assessments and environmental impact reports when power produced is above 10 MW, and they are considered as having a high impact on the environment in existing legislation (115).

(vi) One alternative to traditional damming of rivers that should be considered is instream turbine technology (50, 51), also known as “zero-head.” This offers a less ecologically intrusive means to tap into hydropower without many of the negative externalities identified earlier in this paper. Instream turbines are suitable for rivers with flow velocity exceeding 1 m s^{-1} and can produce steady power (also known as “base power”), since the flow velocity in rivers typically varies much less than wind. Hydrokinetic energy has been used for a long time since the time when river currents were harnessed to crush grains in mills. New small turbine technologies have been quietly developing to harness base power, and large turbine companies (e.g., Voith) are developing smaller turbines and have tested and shown their potential value (116, 117) in six continents and at hundreds of sites (116). Such turbines can be low maintenance, be ecologically friendly to fish, and serve local communities’ energy needs in a green manner. A number of smaller companies (116–118) are testing prototypes and moving toward commercialization. Smart HydroPower has already commercialized 40 instream turbines worldwide (https://www.smart-hydro.de). These companies seem to be conscious of the importance of delivering energy to local communities and of the need to reduce negative impacts of large hydropower dams. Recent corruption scandals in Brazil surrounding Belo Monte, where huge payoffs were made to politicians to approve the dam despite strong evidence against building it, suggest that the motivation for favoring big dams may be tied to complex webs of corruption or particular financial interests. This may be widely true, particularly in places with either authoritarian regimes and/or where financial interests favor large projects, such as big dams, because they offer considerable opportunities to divert funds (119). Of the $11.1 trillion expected to be spent on global infrastructure between 2005 and 2030, $1.9 trillion will be spent on hydropower projects (120), and 60% of those funds involve civil construction and resettlement costs, both areas known to be susceptible to diversion of funds (119). Corruption risks start with undue influence on the selection of sites, undue influence from project developers, bribes, and misappropriation of funds (121). Such corruption undermines public trust in hydropower and undermines its sustainability. The current trend to build large dams in developing countries may be characterized in this manner, and global financial institutions should refuse to be a part of such schemes. Scudder (86) argues that the World Bank Group, as the largest sponsor funding large dams, should take the lead to ensure that their funds meet international standards for environmental restoration and compensation to communities. Voivodic and Nobre (46) suggested that increasing hydropower capacity from the Amazon is not necessary; instead, they propose innovations in biologically inspired technologies (biomass energy production for example) as a way to outgrow the current model of development, which fails to consider the value of biodiversity and cultural diversity in its calculations. Recent assessment of alternatives for the future of energy in Brazil suggests that the optimal scenario is one in which wind energy leads the way, with biomass and solar further strengthening a diversification of the electric sector. Hydropower will continue to provide a substantial foundation of base energy, but the growth in the next two decades is expected to favor wind, biomass, and solar production (52).

The hydropower industry needs sustainability evaluation measures that can stand public and independent scientific scrutiny. Many of these have been proposed but are rarely implemented.

The recommendations of the WCD provide guidelines for social and environmental sustainability for hydropower projects. Since 2001, the WCD guidelines have influenced international accords, financial safeguards, and national laws. For example, the WCD recognized the importance of a full evaluation of energy options to meet energy mix needs before putting a hydropower project on paper. The WCD also promotes alternative siting scenarios for dams that are already assumed will be approved. Too frequently, energy and water planning is secretively guarded by governments (sometimes in collusion with dam builders), is closed to the participation of civil society, and does not follow the WCD guidelines. For hydropower planning to become sustainable, government and industry must prioritize transparency by inviting civil society to the table to discuss and agree on what a country's energy matrix should look like. A growing chorus of scholars across fields of science is calling for modular solutions that combine wind, solar, and hydropower to provide alternative energy sources that are environmentally, socially, and financially desirable (45, 52, 122). Instream technology can provide off-grid energy for isolated communities, such as those in the Amazon and other regions where distance and isolation keep them without access to energy, thereby enhancing their access to inexpensive energy and providing sustainable energy for economic development; that, when combined with solar panels on individual homes to complement the instream hydropower, gives them energy security. One could also install instream turbine parks as a much less disruptive alternative to small dams and produce energy at much lower cost to local communities and the grid.

The most important advantage of hydropower in contrast to other renewable energy sources, like wind and solar, is that it can be dispatched quickly at any time, enabling utilities to balance load variations on the electric distribution system (123). As we move forward in the 21st century, electric companies need to diversify their energy projects even more than they have. The cost of solar and wind is dropping, efficiencies are up, and increasingly, they are price competitive for the energy produced. Hydropower can be part of a sustainable future if it moves away from big dams and toward a combination of instream turbines and diversified energy sources in ways that do not disrupt stream ecology and fisheries and the lives of people on the great rivers of the world. Existing dams in places like Brazil already produce substantial energy for the integrated grid, and what is needed is investment in diversification with solar and wind power. Hydropower has an important role to play as a provider of inexpensive energy complemented by instream hydro and partnering with solar, biomass, and wind to provide power toward a sustainable future.emergence and diffusion of green and sustainable technologies is full of obstacles and has therefore become an important area of research. We are interested in further understanding the dynamics between entrepreneurial experimentation, market formation, and institutional contexts, together playing a decisive role for successful diffusion of such technologies. Accordingly, we study these processes by adopting a technological innovation system perspective focusing on actors, networks, and institutions as well as the functions provided by them. Using a qualitative case study research design, we focus on the high-speed flywheel energy storage technology. As flywheels are based on a rotating mass allowing short-term storage of energy in kinetic form, they represent an environmentally-friendly alternative to electrochemical batteries and therefore can play an important role in sustainable energy transitions. Our contribution is threefold: First, regarding the flywheel energy storage

technology, our findings reveal two subsystems and related markets in which development took different courses. In the automotive sector, flywheels are developing well as a braking energy recovery technology under the influence of two motors of innovation. In the electricity sector, they are stagnating at the stage of demonstration projects because of two important system weaknesses that counteract demand for storage. Second, we contribute to the theory of technological innovation systems by better understanding the internal dynamics between different functions of an innovation system as well as between the innovation system and its (external) contextual structures. Our third contribution is methodological. According to our best knowledge, we are the first to use system dynamics to (qualitatively) analyze and visualize dynamics between the diverse functions of innovation systems with the aim of enabling a better understanding of complex and iterative system processes. The paper also derives important implications for energy scholars, flywheel practitioners, and policymakers.

Keywords: Technology innovation system, Functions of innovation systems, Green technology, Sustainable energy, Flywheel energy storage, Short-term storage, Batteries, Kinetic energy recovery systemEnergy storage has recently come to the foreground of discussions in the context of the energy transition away from fossil fuels (Akinyele and Rayudu, 2014). Among storage technologies, electrochemical batteries are leading the competition and in some areas are moving into a phase of large-scale diffusion (Köhler et al., 2013). But batteries also have a number of environmental issues that are only marginally discussed, such as their hazardous chemical content and “grey” energy (Longo et al., 2014). Environmentally-friendlier alternatives exist at least for some applications (Akinyele and Rayudu, 2014). However, we know little how they develop, what drives or hinders their development, and why they are almost absent from discussions about energy storage. Against this backdrop, we are empirically analyzing the development of a promising clean short-term storage technology: flywheel energy storage (FES). Its operation principle is simple: flywheels store energy in kinetic form in a rotating mass. While low-speed flywheels have been used for years for uninterrupted power system, modern high-speed flywheels (HSF) promise a range of new applications, including the recovery of automobile braking energy and the stabilization of grid operations in the context of higher penetration of renewable energies. FES can represent a clean substitution technology for conventional chemical-based and potentially hazardous batteries in short-term storage applications, as it does not involve hazardous materials, has a very long operational lifetime (millions of full-depth discharge cycles), and has a limited impact during production, operation, and disposal (Hadjipaschalis et al., 2009).

We use innovation systems theory to shed light on the development of FES. This approach emphasizes the role of non-technical aspects to understand technology development (Edquist, 1997), which is seen as complex processes that unfold over time and are influenced by the interaction of a multitude of social, political, institutional, and technological factors (Carlsson and Stankiewicz, 1991). Assuming that a number of key processes need to be fulfilled for innovation system build-up, growth, and maturation (Hekkert and Negro, 2009), we adopt the technological innovation systems (TIS) approach (Carlsson et al., 2002) to capture these processes and draw links to influential contextual elements (Bergek et al., 2015). Positive self-reinforcing dynamics –

motors of innovation – need to overcome system weaknesses for TIS growth and maturation (Jacobsson and Bergek, 2011).

We conducted an explanatory case study (Yin, 2014) providing insights into FES development geographically centered in German-speaking Europe, but also tracing links beyond this region's borders. The findings reveal that modern FES are emerging with very different dynamics in two different sectors. First, in the automotive sector FES is developing well as a braking energy recovery technology and is close to introduction in medium-sized markets in mass transportation. Development was driven by two important motors of innovation: the incubation, and in a latter phase the market motor. Second, in the electricity sector FES is developing in various grid-related applications but is currently stagnant because of two important system weaknesses that counteract the demand for storage. First because of an institutional weakness related with the unclear role FES could play in the transition to a sustainable grid, and second an actor weakness in the form of lacking entrepreneurial and commercial capabilities.

We contribute to two different literature. First, we address the cleaner production and sustainable energy technology literature by providing insights into the development of a storage technology that is more environmentally-friendly than conventional batteries and could possibly serve as a substitute in short-term storage applications. Second, we also contribute to TIS literature. We discuss the determining influence of two contextual structures: industry sectors and competing TIS. And we introduce a new methodological component to the TIS literature by using system dynamics representations to visualize complex TIS dynamics. Finally, we provide strategic insights for practitioners and policymakers.. Flywheel energy storage technology overview

Energy storage is of great importance for the sustainability-oriented transformation of electricity systems (Wainstein and Bumpus, 2016), transport systems (Doucette and McCulloch, 2011), and households as it supports the expansion of renewable energies and ensures the stability of a grid fed with multiple intermittent energy sources (Purvins et al., 2011). Batteries increasingly dominate discourses on energy storage (Akinyele and Rayudu, 2014), but their environmental impact is only marginally discussed (Matheys et al., 2007, Zackrisson et al., 2010). Other promising technologies exist, but, to our knowledge, little is known about how well they are developing. Neglected short-term storage technologies include compressed air, hydrogen, super-capacitors, and FES (Hadjipaschalis et al., 2009, Mahlia et al., 2014). Among these, FES represents an environmentally-friendly option as it is made of non-hazardous basic metals and carbon fibers (although some rare earth elements can appear in the motor-generator). Its operational lifetime of several1 million full depth of discharge cycles (Mahlia et al., 2014) and up to 20 years operational time (Hadjipaschalis et al., 2009) is very long. For short-term storage applications FES is a clean substitution technology for batteries (Liu and Jiang, 2007). In extension of the term "clean technology", we consider FES to be a clean energy storage technology.

Compared to batteries, FES typically have a higher power output (watt), but store less energy (watt-hours) over a short period of time (currently only a couple of hours). With several million discharge cycles, FES have a much longer service life and are significantly lighter, have a smaller size, and occupy less floor space (Piller, 2015). Also, their lifecycle cost is lower than for batteries (Zakeri and Syri, 2015). In some cases, FES can be complementary to batteries, as an FES is more effective at storing and delivering large amounts of energy (watt) over a short-time period. Moreover, when used in combination, they can increase battery lifetime (Dhand and Pullen, 2013). FES also compete with super-capacitors for very short-term storage application (in the seconds to minutes range (Doucette and McCulloch, 2011).

In the literature, three main types of flywheels are distinguished: low-speed, high-speed, and micro-high-speed flywheels. Table 1 captures their main characteristics and differences. First, low-speed flywheels (LSF) are typically made of a steel mass using roll bearings and rotating at speeds varying from 1000 to 10,000 revolutions per minute. They have been commercially available for over 30 years and are a conventional solution when low cost is important but floor space is not. Second, high-speed flywheels (HSF) – a kind of modern "big brother" of LSF (Fig. 1) – are equipped with a rotor made of composite materials and/or steel and low friction bearings. They typically rely on an advanced magnetic system to reduce friction.2 Low friction bearings mean lower inertia losses (therefore higher efficiency) and longer storage duration, up to one day (Wasserman and Schulz, 2011) – with only a fraction of the LSF size (Schaede et al., 2015). In sum, HSF allow the storage of larger amounts of energy in a smaller space and over a longer time. Third, micro-HSF – the "little brother" of the HSF – are used as kinetic energy recovery systems (KERS). They were first developed to recover the braking energy of race cars and then buses. They are light, compact, and store relatively little energy, but have a high power output. Compared to their larger counterparts, they are safer but less efficient. Given the bumpy conditions of the road environment in which micro-HSF operate, less advanced but more shock-resistant roller bearings are used, which decreases efficiency, but this is a minor issue as braking energy abounds in vehicles.. Technological innovation systems
Systems approaches to policymaking appeared in the 1970–1980s as a reaction to the perceived inadequacies of neoclassical market-based climate policies, which rest on R&D subsidies and market-based economic incentives (Bergek et al., 2008a, Jacobsson and Bergek, 2011). In this context, scholars argued that adopting a systems approach can lead to a better understanding of holistic, complex, "wicked" problems to inform interventionist climate change policies. In the past years, several innovation system approaches emerged, including national innovation systems (NIS), regional innovation systems (RIS), sectorial innovation systems (SIS) and technological innovation systems (TIS) (Chang and Chen, 2004). They are all rooted in evolutionary economics (Nelson and Winter, 1982), but they differ in focus. TIS is used to study the emergence of new technologies as an individual and collective social process (Carlsson et al., 2002). A TIS can defined as a "network(s) of agents interacting in a specific technology area under a particular institutional infrastructure for the purpose of generating, diffusing, and utilizing technology" (Carlsson and Stankiewicz, 1991: 21). It is intended to inform policymaking on how to manage, influence, and accelerate technology evolution (Foxon and Pearson, 2008). In academia, it gained popularity with the desire to understand the emergence of renewable energies (Jacobsson and Johnson, 2000) and, more recently, clean-tech in general, also in developing countries (Gosens et al., 2015).

An innovation system is composed of several structural elements (Table 2): actors in the whole supply chain, networks, institutions, and – in the case of TIS – also technology (Bergek et al., 2008a, Carlsson et al., 2002). Being embedded in a wider socio-technical environment (Granovetter, 1985), the innovation system interacts with wider contextual structures (Jacobsson and Bergek, 2011, Markard and Truffer, 2008). Recent research suggests considering four types of contextual structures depending on the intensity of the interactions Bergek et al. (2015). First, the focal TIS may coevolve with other TIS, which could influence their reciprocal dynamics. Second, TIS can be related to the structures and dynamics of the sector(s) of which it is a part. Third, a TIS is always localized somewhere and, while the analytical focus is on technology, geographical aspects may also be relevant. Fourth, political contexts can play an important role, for instance in the availability of public resources and societal legitimacy.