Dilekli N., Cazcarro I. 2019. **Testing the SDG targets on water and sanitation using the world trade model with a waste, wastewater, and recycling framework.** ECOLOGICAL ECONOMICS. 165. DOI (10.1016/j.ecolecon.2019.106376).

Testing the SDG Targets on Water and Sanitation Using the World Trade Model with a Waste, Wastewater, and Recycling Framework

Abstract

In this article, we employ an extended world trade model and rectangular choice of technology (WTM/RCOT) framework, which minimizes global factor costs subject to satisfying final demand and respecting region-specific factor constraints, to calculate the economic costs of achieving the United Nations Sustainable Development Goals (SDGs) for water and sanitation. We estimate how achieving these goals will affect factor use, trade balances, scarcity rents, and production in 19 regions of the world, drawing on an expanded database developed from the GTAP9 database, the developed model involves 64 technology columns and 74 rows of factors of production. On a theoretical level, this model contributes to the existing literature on the topic by using endogenous cost estimates that consider shifts in production and factor scarcity rents and by considering recycling and wastes within an input-output model, in which wastes can be modelled as input resources as well as waste outputs. We find that the additional factor costs of meeting the water and sanitation targets of the SDGs exceed US$100 billion annually, with a total cost of US$3.3 trillion from 2015 to 2030. These figures are similar to other recent works on the subject despite methodological differences. It also suggests that the worldwide SDG targets can be achieved with moderate costs relative to the total global GDP, especially in comparison to the high estimated cost of inaction. Predictably, in areas working toward water and sanitation SDGs (areas such as Sub-Saharan Africa, regions in South Asia, etc.), factor use costs increase, but not commensurately with the growth of coverage—some regions, such as areas of South America, notably have higher factor use costs along in proportion to the coverage. Indeed, Sub-Saharan Africa, which needs the highest increase in coverage, will not likely have as large increases in factor uses and would barely get scarcity rents. In general, regions with higher SDG targets will require further trade, especially additional imports of inputs such as chemicals and energy products. This trade will increase factor earnings in factor rich regions such as the European Union, Japan, and Korea.

Keywords: World Trade Model, input-output scenario analysis, SDGs, waste, water, sanitation.

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1. Introduction

As the global population grows and per capita resource consumption increases, humanity faces interconnected challenges related to water, food, energy, and environmental sustainability. Recognizing these challenges, many researchers have turned their attention toward identifying more sustainable strategies for global resource management. See, for example, the work of Bengtsson et al. (2018), Heinz et al. (2017), Hubacek et al. (2016), Koltun (2010), and Krausmann et al. (2017).

In this paper, we employ an integrated World Trade Model and Rectangular Choice of Technology Model (WTM/RCOT) to assess the economic costs and the changes in factor use, trade balances, scarcity rents, and production that would be required if the world is to meet the United Nations Sustainable Development Goals (SDGs) related to water and sanitation.

In 2015, the United Nations promulgated the SDGs as a universal call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity. The Goal 6 targets of the SDGs aim to achieve universal and equitable access to safe and affordable drinking water, sanitation, and hygiene by 2030. These goals are ambitious. In 2008, nearly 900 million people did not receive drinking-water from improved water sources (WHO/UN, 2010), and in 2015, over 2.4 billion people lived without access to improved sanitation facilities (UNICEF, 2015). As of 2015, at least 1.8 billion people rely on a source of drinking water that is contaminated by feces, and of the wastewater produced by human activities, more than 80% is discharged into rivers or seas without any pollution removal (UNICEF, 2015). The consequent impacts to human health include the deaths of 1.8 million children under the age of five every year from water-related diseases (Corcoran et al., 2010) and the deaths of a total of 2.2 million people annually from diseases, such as cholera, typhoid, and dysentery, that are spread by contaminated water and poor hygiene. Further suffering is threatened by worsening freshwater stress, which is exacerbated by population growth, seasonal droughts, and global climate change (UN_Water-FAO, 2007; Watkins et al., 2006). To move from the current state of affairs to the world envisioned by the SDGs, humanity must make substantial investments in wastewater treatment and sanitation. Along this line of thinking, we pose the following research question: Is it physically feasible to satisfy the SDGs regarding safe water and sanitation by 2030? If so, what infrastructure systems and technologies would need to be put in place and how substantial must these investments be, though? What changes in the global economy will they entail?

In this work, we address these questions through a WTM/RCOT framework extended for dealing with waste and necessary capital investments. We study how achieving the SDGs requires financial costs and affects factor use, trade balances, scarcity rents, and production, under three different types of scenario (each with four variants). The first type

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of scenario deals with the hypothetical accomplishment of the United Nation’s previous Millennium Development Goals (MDGs), which were the precursors to SDGs in the period from 2011-2015. Secondly, the actual-historical accomplishment of the past MDGs (the real trend) is run for the same period, serving as the baseline for the third scenario. The third type of scenario, to which we dedicate most of our attention, uses the second type of scenario as a baseline to project the economic costs and consequences of meeting the SDG targets related to water supply (the provision of access to healthful, accessible, and affordable water) and sanitation (the evacuation, treatment, regeneration, and reuse of wastewater).

2. Literature Review

Since the availability (or lack) of clean water has implications for the environment, human health, and economic activity, there is significant interest in the costs and consequences of providing clean water, particularly to meet SDG Goal 6.

Existing studies—when accounting not just for basic water supply but also for advanced systems, such as in-house sewage and regulated in-house piped water supplies with quality monitoring—estimate that providing water and sanitation for all would require between US$2 billion and US$100 billion annually (Annamraju et al., 2001; *Financing Water For All*, 2003; Hutton and Haller, 2004; World-Bank, 2003). The considerable variation between these costs is due to high uncertainty related to treatment technologies, ambiguities in defining the targets in quantifiable terms, lack of data, and the use of different methods and assumptions. As a summary of existing conclusions, we represent in Table S1 the major studies estimating the costs for the water and sanitation targets of MDGs and SDGs.

As reviewed by Toubkiss (2006), the costs of reaching water and sanitation targets are often underestimated, with studies regularly failing to include the costs for maintaining, rehabilitating, or replacing existing infrastructure, which may be aging or neglected. In an additional source of possible error, existing studies rely on exogenous pricing to calculate global costs. The accurate treatment of recycling and waste has also been a challenge, particularly the modelling of wastes that can be input resources as well as waste outputs. In short, the actual costs and consequences of achieving water-related SDGs are still contestable.

To make models of water and sanitation more accurate and reliable, researchers have developed several promising approaches. To increase the accuracy of price estimates and address inaccuracies introduced by exogenous pricing, IO analyses can calculate shifts in production and factor scarcity rents to determine costs endogenously, addressing scenarios that include changes in demands. IO models can also address issues of recycling and waste. Examples of such work include Duchin's (1990a) seminal work, which, within

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the framework of the environmental IO model, included an example with two types of wastewater abatement processes, which respectively treat wastewater containing high and low levels of biological solids; the WIO model (Kondo and Nakamura, 2003; Nakamura, 1999; Nakamura and Kondo, 2002), which is also a milestone in the field and is used in the literature to study the relation between physical and monetary IO tables (Dietzenbacher, 2005; Giljum et al., 2004; Suh et al., 2009; Weisz and Duchin, 2006) and material flow analysis and related topics in industrial ecology (Suh and Kagawa, 2005); and the research of Kagawa (2005), Kondo and Nakamura (2005), Nakamura et al. (2007), Nakamura and Kondo (2006), Nakamura and Nakajima (2006, 2005), Takase et al. (2005), and Yokoyama et al. (2006), who developed a WIO linear programming model (WIO-LP), a decision analytic extension of the WIO.

The WIO model is an extension of the conventional IO model that explicitly considers the interdependence between the flow of goods and the flow of waste in the whole economy. It is a generalization of the Leontief–Duchin environmental IO model (Duchin, 1990; Leontief, 1970) with emphasis on waste flows. The WIO model provides a general framework for hybrid life cycle assessment (LCA) involving waste management and recycling. A number of LCA and life cycle inventory analyses of wastewater treatment have been carried out based on process data. See, for example, Almanza Ramirez (2012), FranklinAssociates (2009), Meng et al. (2010), Muñoz et al. (2017), and Risch et al. (2015). Lin (2011, 2009) proposed it as an extension to a hybrid IO model designed to analyze both the generation and treatment of wastewater. Lenzen and Reynolds (2014) incorporated a supply-use formalism, resulting in waste supply-use tables, and multiregional WIO has been proposed for the study of steel (Pauliuk et al., 2017).

Additionally, Dilekli and Duchin (2015) explicitly used negative coefficients within a WTM/RCOT to represent government subsidies and useful chemical byproducts generated by the cellulosic ethanol sectors. Their successful application of negative coefficients demonstrates that ability to represent recycling and waste treatment within a WTM/RCOT model.

In this section, we identified that most of the IO studies focus on the small scale or bottom-up aspects (water and sanitation technologies and their costs, types of connections of households, factor uses, etc.). However, the ramifications to the global economy due to changing flow of goods and factor prices has not been sufficiently clarified, especially in the context of wastewater treatment. We therefore pay a substantial effort to discover the global patterns while incorporating the smaller scale data for accuracy. Building on these previous studies, this paper adopts a multiregional WTM/RCOT as an optimization model and introduces basic elements of the WIO and dynamic IO models to analyze water and sanitation in relation to SDGs. In addition to this paper's work introducing WIO and

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dynamic IO to WMT/RCOT, this paper also differs from most articles on water pollution (including thermal pollution) and IO (see Duarte et al., 2002; Duarte and Sanchez-Choliz, 1998; Ni et al., 2001; Okadera et al., 2006, Chenoweth et al., 2014; Daniels et al., 2011; Duarte and Yang, 2011, Dilekli et al., 2018) by posing water sanitation as the central object of study.

3. Materials and Methods

This study employs an extended WTM/RCOT framework that incorporates WIO, IO, and an updated database built upon the GTAP9 database developed by Narayanan et al. (2015, 2012). This extended model is used to explore three main scenarios, each with four variables, for water treatment and sanitation.

3.1 The Extended WTM/RCOT

The WTM is a linear program that minimizes global factor use subject to satisfying final demand and respecting region-specific factor constraints (Duchin, 2005). A model solution reflects comparative advantage generalized to the case of m regions, n sectors, and k factors. The WTM here incorporates the rectangular choice-of-technology (RCOT) model (Duchin and Levine, 2012, 2011) that makes the endogenous choice among technologies. Each region's matrix of intermediate input coefficients is rectangular in that it includes a column for each alternative technology, but only a single row for each of those deliveries, like a typical IO matrix, on the assumption that the consumer is indifferent to the way the product was produced. The WTM logic assumes that production takes place in the relatively lowest-cost regions, and the RCOT logic assumes that the producing regions use their relatively lowest-cost technological options, subject to constraints imposed by limited factor endowments. A resource (or other factor of production) that is fully utilized in a given region incurs a scarcity rent in addition to the exogenous portion of its price.

The model solved over time we develop here works with matrices and vectors: fixed (over time) $\mathbf{A}_i^*$ matrices of intermediate input requirements, and $\mathbf{F}_i^*$ matrices of factor inputs per unit of output or final demand and $\boldsymbol{\pi}^*_i$ vectors of factor prices; with exogenous variables including $\mathbf{y}_i$ vectors of domestic final demand; $\mathbf{k}_i$ vectors of accumulated (i.e. new capital investment for water technologies), $\mathbf{R}_i$ matrices of replacement capital investment (amount of capital goods produced by sector n and held by technology t that must be replaced in order for technology t to produce a unit of output during a year) for water technologies, $\mathbf{f}_i$ vectors of factor endowments,; and three vectors of endogenous variables including $\mathbf{x}_i$ vectors of output; $\mathbf{p}$ vector of world prices, and $\mathbf{r}_i$ vectors of scarcity rents on fully utilized factors, for each region i. The parameters (exogenous) and endogenous

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variables are shown in Supporting Information (S) Table S2. They are modified to reflect each type of scenario. Additionally, they are modified dynamically for each annual time step since the model is run over a time series.

The objective function (1) of the WTM/RCOT primal model minimizes the global factor use cost, adding to the usual component of factors of production per unit of output, $\mathbf{F}^*_{i,int}$, the vector $\mathbf{F}^*_{i,y}$ of direct uses (or waste) per unit of final demand ($\mathbf{y}^+_i$ being the normalized vector of final demand in monetary units). The matrix equation summing over regions (2) assures that global final demand is satisfied, (3) imposes factor constraints in each region by limiting resource use both for intermediate production and final demand, and (4) assures that all outputs are non-negative.

$$\min\ Z = \textstyle\sum_i \boldsymbol{\pi}^{*\prime}_i (\mathbf{F}^*_{i,int}\mathbf{x}^*_i + \mathbf{F}^*_{i,y} \sum_{\boldsymbol{n}} \mathbf{y}^+_i) \qquad (1)$$

subject to

$$\textstyle\sum_i (\mathbf{I}^* - \mathbf{A}^*_i - \mathbf{R}_i)\mathbf{x}_i = \sum_i \mathbf{k}_i + \sum_i \mathbf{y}_i \qquad (2)$$

Based on equation 1, the solution is driven by $\boldsymbol{\pi}^{*\prime}_i \mathbf{F}^*_{i,int}\mathbf{x}^*_i$ as in the original formulation of the WTM given that both $\mathbf{F}^*_{i,y}$ and $\mathbf{y}^+_i$ are exogenous (computed "outside of the model") for each run. They mainly function as factor constraints as shown in Equation 4. In equation 2, $\mathbf{R}_\mathrm{i}$ is simply defined for the columns of water supply and treatment technologies **t**, while arbitrarily small values are introduced in the cells of the sectors with the associated technologies (quasi main diagonal). Similarly, this is also applied for $\mathbf{k}_i$, reflecting the capital produced in the different sectors to increase the capacity of the water supply and treatment technologies **t**. Our $\mathbf{k}_i$ plays the role of what was defined as $\mathbf{B}^*_i\mathbf{o}$ (investment capital matrix for region **i** times the increase in the productive capacity between periods period_{t-1} and period_t) in the seminal works on dynamic IO models, such as Duchin and Szyld (1985) and Leontief and Duchin (1986). Here our formulation is simpler, without any forward-looking projected capacity expansion. In our application $\mathbf{R}_i$ and $\mathbf{k}_i$ are defined solely from the gathered data on the necessary investment for capital replacement in a year, and on the cumulative new investment in water and water treatment sectors to meet the SDG targets (Refer to Figure S2 for amounts accounted for on this last aspect).

Commented [ND1]: I think this may be confused with t, technology two lines above. That's the reason I changed it accordingly.

It should be noted that, we can derive the following equation for the study of the net exports ($\mathbf{e}$) by each region i after the execution of the model:

$$(\mathbf{I}^* - \mathbf{A}^*_i - \mathbf{R}^*_i)\mathbf{x}_i = \mathbf{k}_i + \mathbf{y}_i + \mathbf{e}_{\boldsymbol{i}} \qquad \forall i \qquad (3)$$

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The equation on factor, waste, or any represented pressures with the $\mathbf{F}^*_{i,int}$ matrices and $\mathbf{F}^*_{i,y}$ vectors is formulated as follows, satisfying also the condition of non-negative (equation 5) production:

$$\textstyle\sum_t (\mathbf{F}^*_{i,int}\,\mathbf{x}_i) + \mathbf{F}^*_{i,y}\sum_n \mathbf{y}_i^{+} \le \mathbf{f}_i, \qquad \forall i \qquad (4)$$

$$\mathbf{x}_i \ge 0 \qquad \forall i. \qquad (5)$$

Commented [ND2]: What is this?

The inclusion of $\mathbf{F}^*_{i,y}$ aims to address how to best reflect consumption and waste occurring at household level, which is not ordinarily captured through factor use for intermediate production. When people draw water from a well or pick tree branches for daily activities, it can as well be considered an economic activity and could be reflected in $\mathbf{F}^*_{i,int}$ for more accurate accounting and analysis. Additionally, this allows the model to be more explicit and modular (instead of confounding the component $\mathbf{F}^*_{i,y}\sum_n \mathbf{y}_i^{+}$), while accounting for this purpose and better limiting the use of the factor endowment, $\mathbf{f}$[2].

Alternatively it is possible to formulate the equations separating the matrices of net waste of sectors $\mathbf{G}^*_{i,int}$ and of net waste of households $\mathbf{G}^*_{i,y}$ from $\mathbf{F}^*_{i,int}$ and $\mathbf{F}^*_{i,y}$, so that equation (4) would read be $\sum_t ((\mathbf{F}^*_{i,int} + \mathbf{G}^*_{i,int})\mathbf{x}_i) + (\mathbf{F}^*_{i,y} + \mathbf{G}^*_{i,y})\sum_n \mathbf{y}_i \le \mathbf{f}_i, \ \ \forall i$. However, we prefer to keep the original formulation because in some cases a specific row in $\mathbf{F}$ —for example, water of a certain low quality— is an input to a technology (positive value) and a waste output for another (which needs a higher quality type and returns this lower quality type, with a negative coefficient). We could also consider the matrix of intermediate coefficients of the waste processing sectors ($\mathbf{A}^*_{i,II}$) separately from $\mathbf{A}^*_i$, as in Nakamura and Kondo (2002), but we keep the formulation with the whole $\mathbf{A}^*_i$, just noting that while most other sectors typically show negative coefficients for waste output rows, these processing sectors typically will have positive coefficients in waste output rows (or in the case of primary and secondary waste water treatment, in the row of low quality water). $\mathrm{f}_{k,i}$, the waste endowment is either zero or a negative value (e.g. environmental regulations), for each type *k* of waste.

The model represents a compact version of a multi-sectoral and multi-regional world economy that is parameterized to run scenarios. Because it is based on the logic of comparative advantage, it does not require the parameterization of trade or equations quantifying imports and exports as functions of other variables.

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[2] In scenario analysis this also needs to be considered, since it requires a parameter specifying the relation between the changes in the consumption by sectors affecting the resource use of an element of $\mathbf{F}^*_{i,y}$ to total final demand (e.g. the relation of the change in $\mathbf{F}^*_{i,y}$ when changing the water demand with respect to total final demand).

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Additionally, we introduce constraints on trade for non-traded[3] or partially traded sectors, so that for a sector *n*, the equation (2) has to be met fully (or partially) for each region. Also the benefit-of-trade constraint assures that a region will enter into trade only to the extent that its imports at no-trade prices are worth at least as much as its exports. This constraint involving the no-trade (model) price $\mathbf{p'}^{\mathrm{ntm}}{}_{\mathrm{i}}$, is depicted in the following equation:

$$\sum_{n,t} (\mathbf{p'}^{\mathrm{ntm}}{}_{\mathrm{i}}(\mathbf{I}^{*} - \mathbf{A}_{i}^{*})\mathbf{x}_{\mathrm{i}} \leq \sum_{n} (\mathbf{p'}^{\mathrm{ntm}}{}_{\mathrm{i}}\,\mathbf{y}_{\mathrm{i}}) \qquad (6)$$

3.2 Waste and Recycling Conceptualization within the WTM/RCOT

The application in the WTM/RCOT for waste and recycling proposed here borrows certain conceptualizations from WIO in the representation of waste and waste treatment processes, with parsimonious representation of key processes. The model used allows work with physical units. It enables the addition of new and alternative technologies, such as alternative waste treatment technologies including composting (C), incineration (I), landfilling (L), shredding (S), gasification (G), and alternative recycling (R). In this application, we develop technology columns for each recycling technology in A and F matrices. These additional columns correspond to the "Allocation Matrix" in WIO and represent the use of the treated/recycled/re-used material.

We represent returns or byproducts as raw materials (factors) as well as commodities using **F** and **A** matrices. According to the nomenclature of the WIO, waste "inputs" (Wi) are represented by positive values (+), and waste "outputs" (Wo) are represented with negative values (-). These values are in physical units (typically tons, or m^3, etc.) per unit of output. We identify two types of waste output: waste output that can be recycled into a useful material (represented with a + value) by a treatment technology and waste output that cannot be recycled and that is subject to the carrying capacity of the system (e.g., limitation of landfill area or an environmental regulation). In the latter case, an **f** constraint is introduced with a negative value to limit its generation.

WTM/RCOT provides endogenous mechanisms to provide feasible solutions. We accordingly construct recycling technologies to ensure factor endowments can be available as much as needed by economies, provided that the costs are met. The model also allows for the utilization of the price ($\boldsymbol{\pi}_{\mathrm{i}}$) of the factors and net waste input, as explained by Nakamura and Kondo (2006) and Nakamura and Kondo (2009). Additionally, waste from households can be and is accommodated to impose constraints

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[3] These sectors include Water distribution, Water treatment 1, Water treatment 2, Construction, Communication, Recreational and other services, Public Administration, Defense, Education, Health and Dwellings.

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by introducing the vector $\mathbf{F}_{i,y}^{*}$ of households' factor use per unit of final demand, which also implies a factor use in absolute terms $\mathbf{F}_{i,y}^{*}\mathbf{y}_{i}^{*}$, affecting the constraint on endowment (equation 4). Previous WTM applications did not represent direct waste (of food to the corresponding row, or other waste through toilets as output of low-quality water) or emissions directly imputed to households (transport, such as cars, electricity consumption, etc.); this extension makes it possible to incorporate this important feature.

In the Figure S1, we provide a more general and detailed explanation and representation of waste in the WTM/RCOT. In Figure 1 below we provide a conceptual database to represent water pollution and water treatment with relevant technologies for a given sector based on their ability to use low-quality (L), medium quality (M), or high quality (H) water. This defines a framework on how the sludge, water treatment process, and water quality are represented. Sewage sludge is produced from the treatment of wastewater in sewage treatment plants. It is usually treated by one or several treatment steps. Following treatment, it is either landfilled, incinerated, applied on agricultural land, or, in some cases, retailed or given away.

If water cannot be used due to water quality and quantity requirements, either wastewater treatment takes place, or production needing clean water moves to another location. In order to meet drinking quality of a certain standard, water is typically purified to remove undesirable chemicals, biological contaminants, suspended solids, and gases. Also, households demand the volumes supplied by the water sector (understood in general terms, these volumes can be piped water, as is typical in developed countries, or "basic" from wells), and households also demand sanitation (water should be accessible on premises, available when needed, and free from contamination). Sanitation can be either "basic" (provided from our first water cleaning technology) or "safely managed" (provided from our second water cleaning technology).

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Figure 1. Conceptual Database for the SDG on Water and Sanitation Scenario

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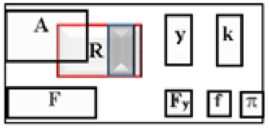

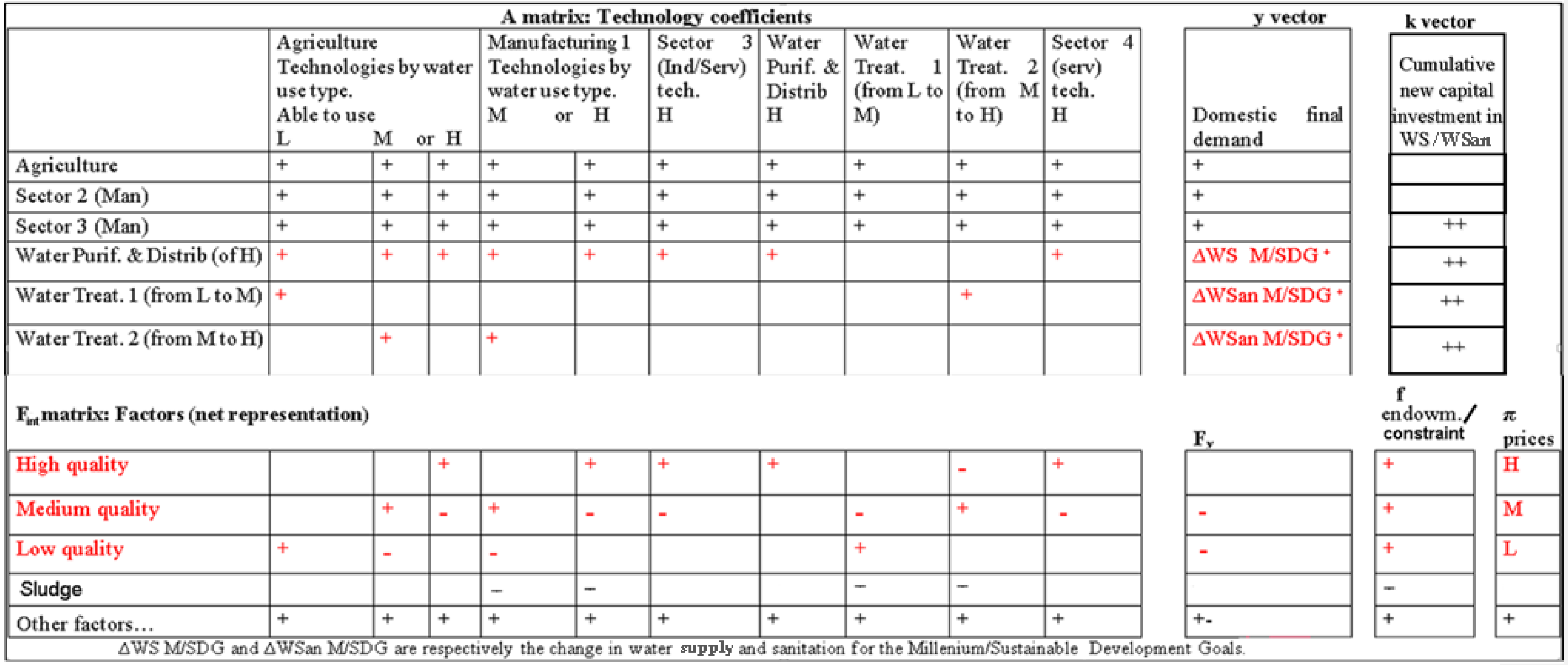

	A matrix: Technology coefficients										y vector	k vector
	Agriculture Technologies by water use type. Able to use L	M	or H	Manufacturing 1 Technologies by water use type. M	or H	Sector 3 (Ind/Serv) tech. H	Water Purif. & Distrib H	Water Treat. 1 (from L to M)	Water Treat. 2 (from M to H)	Sector 4 (serv) tech. H	Domestic final demand	Cumulative new capital investment in WS / WSan
Agriculture	+	+	+	+	+	+	+	+	+	+	+	
Sector 2 (Man)	+	+	+	+	+	+	+	+	+	+	+	
Sector 3 (Man)	+	+	+	+	+	+	+	+	+	+	+	++
Water Purif. & Distrib (of H)	+	+	+	+	+	+	+			+	ΔWS M/SDG *	++
Water Treat. 1 (from L to M)	+								+		ΔWSan M/SDG *	++
Water Treat. 2 (from M to H)		+		+							ΔWSan M/SDG *	++

F_{int} matrix: Factors (net representation)											F_y	f endowm./ constraint	π prices
High quality			+		+	+	+		-	+		+	H
Medium quality		+	-	+	-	-		-	+	-	-	+	M
Low quality	+	-		-				+			-	+	L
Sludge				–	–			–	–			–	
Other factors…	+	+	+	+	+	+	+	+	+	+	+-	+	+

ΔWS M/SDG and ΔWSan M/SDG are respectively the change in water **supply** and sanitation for the Millenium/Sustainable Development Goals.

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Source: Own elaboration.

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3.3 Database

The building of the database departs from the work of Cazcarro et al. (2016) with the following improvements: 1) The underlying economic database was updated to GTAP9 from GTAP8); 2) Data for vectors $\mathbf{k}_i^*$ and matrices $\mathbf{R}_i^*$ of new investments and replacement matrix (see the Supplementary Material, SM, subsection "Capital replacement (R) and new capital investment (k)") were added; 3) The current database includes future projections on population, income per capita, convergence of technologies, and requirements for water and sanitation targets accomplishment (see SM, subsection "Actual accomplishment (2011-2015) and Scenario design of SDGs for the period 2015-2030"); 4) The water treatment technologies data has been also revised for a more updated representation for each region. In addition, factor uses and wastes have been differentiated separately for the industrial sectors ($\mathbf{F}_{i,int}^*$) and the households ($\mathbf{F}_{i,y}^*$).

Accordingly, the compilation of the baseline data starts from standard IO matrices in monetary units from the GTAP9 database (Narayanan et al., 2015, 2012) featuring the years 2004, 2007, and 2011 as reference years. We construct the database by utilizing the most recent set of base information available for each region. We organize the data into 19 regions and by 50 sectors (Table S3 and Table S4), to obtain the **A** matrix of intermediate deliveries, the **y** matrix of final demand (being a vector in our database), and the **F** matrix of factor use. Each of these elements was then disaggregated according to the study needs. In particular, the disaggregation of the sectors in $\mathbf{A}_i^\star$ and $\mathbf{F}_i^\star$ is based on general and country-specific engineering and cost information (labour, capital, intermediates, etc.), especially of the water supply and water treatment, appropriate to represent the technologies (columns).

We made use of a range of data sources to develop water related parameters and variables (Europe-Innova, 20103; Libhaber, 2008; Torres, 2012; Von Sperling and Chernicharo, 2005; WHO, 2012). Supplementary sources for individual regions are identified in Table S1 in the SM in Cazcarro et al. (2016), which have been updated with information from additional works (OECD, 2018a; Plappally and Lienhard, 2013; Sperling, 2007; WWAP, 2017). We used unit costs of water treatment alternatives from Danilenko et al. (2014) and Sipala et al. (2003). Capital costs per person served in 2015 are obtained per water and sanitation technology for each country from Hutton and Varughese (2016), distinguishing rural and urban populations, which we multiply by the population served by combining the share of rural and urban coverage (JMP, 2018) and the rural and urban population (UN, 2018, 2017).

We construct the wastewater coefficients for the $\mathbf{F}_i^\star$ matrix using the figures in the literature (Flörke et al., 2013; Drechsel et al., 2015; FAO, 2018; GWI, 2017; Mateo-Sagasta et al., 2015; Sato et al., 2013; WWAP, 2017). We elaborate Table S5 with the

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baseline volumes of the produced municipal wastewater, water treated (the output of the water treatment sectors[3]), and water supplied (the output of the water supply sector).

74 rows of factors of production were added to the database as listed in Table S6. In the SM further information is provided in the section "database additional sources and description". We may highlight here that the $\mathbf{k}_i^*$ vector is built based on the estimated necessary new investments to achieve the targets (Hutton and Varughese, 2016), using the investment distributions by sector (OECD, 2018b[4]) to develop the water treatment technologies. The vector is adjusted for each region using specific countries data (e.g. BBVA&IVIE, 2018; BEA, 2018; INEGI, 2017; INSEE, 2018; Mas et al., 2013; NBSC, 2018). Matrices $\mathbf{R}_i^*$ are built with relevant non-zero values for the water technologies columns dividing the Consumption of fixed capital (CFC, obtained from the cited specific country sources, and the Series on capital stocks[5], the OECD (2018b, "9A. Fixed assets by activity and by asset, ISIC rev 4").

Notably, the elements of the database and the constraints play a very important role in the replication of the real-world results to construct a baseline scenario, which does not identically reproduce the raw input-output data as this was not "forced" by an array of constraints. This would be against the purpose of this experience, which is to obtain instructive insights using few variables that are conducive to interpretation. In spite of this, the results are not inconsistent the state of the world economy e.g. in terms of the share of the output of a technology in a region in the total of the output of the region, or in the total output of that technology in the world. This is due to the systematic checks, notably to avoid anomalous specializations. In addition to the obtained multi-regional results of productions that are in line with the raw data, the trade flows are also consistent, matching the exporting/importing properties of world regions. Additionally, the deviation of the total exports and imports is less than 5% worldwide.

3.4 Scenario Design for Water Treatment and Sanitation

Our objective for scenario analysis is to establish a baseline first and then investigate the feasibility of SDG targets while observing economy wide impacts across the globe. Our

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[4] "8A. Capital formation by activity, ISIC rev4".

[5] Series on capital stocks tend to use a "perpetual inventory" approach to record the accumulation of new capital and the discarding of existing assets. The former departs from an observation in time 0 (they tend to be historical series), adding each year's gross investment, and considering for depreciation the lifetimes of different capital goods.

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main analysis is established from the year 2015, which reflects the current state of water access and treatment as well as the rest of the economy.

Next, we design an extensive and iterative series of SDG scenarios. Our SDG experiment simulates the achievement of SDG targets within the world economy every year between 2015 and 2030. The achievement of the SDGs is expected to imply investment costs, as we have described in the scenario design, and which we exogenously introduce into the $\mathbf{k}_i^*$ vector. Additional recurrent costs occur endogenously due to operation and maintenance, as most studies on the topic have studied. Each of the main three scenarios is run with all combinations of four variables.

Target Type: SDG defines two types of drinking water services that are used to construct our scenarios: basic and safely managed. Basic service refers to an improved water resource within 30 minutes' round collection time. Safely managed refers to access to drinking water on premises and access to sanitation services that safely dispose of human waste.

Population Growth: For each scenario year, the final demand has been adjusted based on three levels (Low/Medium/High) of population projections (2015-2030) (UN, 2018).

GDP Growth: Along with population growth, three distinct GDP per capita growth projections are used to update final demands. GDP growth data was obtained from the *SSP Public Database Version 1.1* (the Shared Socioeconomic Pathways SSP2, SSP3 and SSP5, to represent the low, medium and high variants, respectively) (Kriegler et al., 2012; O'Neill et al., 2011, 2014; OECD, 2018b).

Technology Adoption: For each year, we implement two options in terms of technology adoption (No / Yes), because of the investment stimulation. Developing regions reach the average technology of the developed regions (converging the column coefficients of $\mathbf{A}^*$ and $\mathbf{F}^*$, progressively accomplishing it the 15th year).

The first three variables modify the main exogenous variable, $\mathbf{y}$, and the last variable modifies the water technologies columns $\mathbf{A}^*$ and $\mathbf{F}^*$. As a result, we develop 36 scenarios based on the combinations of the four variables for each year between 2015 and 2030. We provide details of the scenario design in the SM ("Actual accomplishment (2011-2015) and Scenario design of SDGs for the period 2015-2030") .

4. Results

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Figure 2 summarizes the global paths of population coverage for the baseline and SDG scenarios. Figures S2 and S3 show population coverage for the different regions modelled here.

Figure 2: Population (millions of people) targeted for coverage (under the MDGs and SDGs) and actually covered

Source: Own elaboration from Hutton and Bartram, 2008; Hutton and Varughese, 2016; JMP, 2018; UN, 2018, 2017; WHO, 2012.

The scenarios presented in the following sections depart from the new baseline for the year 2015.

4.1. Global costs and factor uses

To evaluate global costs associated with achieving SDG goals, we first look at the factor use costs, which are generated from increased final demands and the increased factors and inputs (goods and services) required to meet the demands. From 2015 to 2030, global factor costs (reflected as the global value of Z, the objective function) increase from US$62 trillion in 2015 to US$135.4 trillion in 2030 (2015 prices). Under scenarios with the medium variants of population growth and Gross Regional Product (GRP) per capita growth (equivalent to the SSP2 of IIASA), global factor use costs reach to approximately

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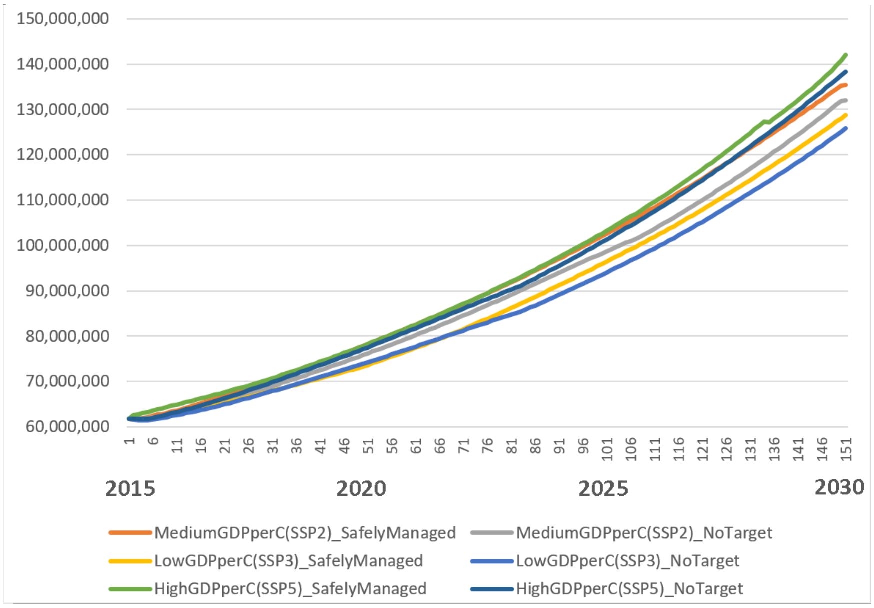
US$132 trillion in 2030 (2015 prices). As shown in Figure 3, the scenario with high population growth and low GRP per capita growth (path SSP3) involves smaller costs than a scenario with low population growth and relatively high GRP per capita growth (path SSP5). The differences in global costs due to these differences in paths are higher than the differences due to the accomplishment of the SDG targets.

Under the variant of technological convergence, it requires a total of US$3.4 trillion (2015 prices) from 2015 to 2030 in order to accomplish the SDGs under the safely managed pathway with medium growth in GDP per capita. This total expense represents about 0.24% of the global GDP on average. Under the scenario variant of low growth in GDP per capita (SSP3), the total cost from 2015 to 2030 is US$3 trillion; with high growth in GDP per capita (SSP5), the cost is US$3.7 trillion (2015 prices). Accomplishing the "Basic" SDGs with medium growth in GDP per capita (scenario variant SSP2) requires a total of US$1.9 trillion (2015 prices) between 2015 and 2030.

Figure 3: Change in the Global Value of Z between 2015 and 2030 with the technological convergence variant (million US$).



Source: Modelling results.

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For SDG water supply targets, the area with the largest need to increase coverage is the region of Sub-Saharan Africa, followed in order by Southeast Asia, South Asia, Malaysia and Indonesia, and India. For the "Safely managed" sanitation targets, the highest increase in coverage is required in South Asia, followed by the following regions in Asia: India and China.

Increasing coverage in these regions does affect factor uses and increase costs, but the global costs from factor use are dominated by the regions of US, EU, and China, followed at a distance by Japan and Koreas. Figure S3 shows the absolute change in factor use costs ($\boldsymbol{\pi}_i'(\mathbf{F}_{i,int}^{*}\mathbf{x}_i^{*}+\mathbf{F}_{i,y}^{*}\mathbf{y}_i^{*+})$) for the 19 regions from 2015 to 2030 (safely managed targets, medium population growth and GRP per capita, SSP2). Under the same scenarios, Figure S4 shows the change by factors. More interesting may be the percentage changes in factor use costs, which are shown in Figure 4. In the achievement of the SDGs for water and sanitation, North Africa and the Middle East (16MEAS_NAF_RSA), as well as East Asia, South America, China, and South Asia, would experience the highest increases in factor use costs.

Figure 4 reflects changes in population and GRP per capita, based on the SDG water and sanitation accomplishment. Thus, Figure 5 has been developed to isolate the comparison by showing the differential change in factor use costs (comparing safely managed target vs. no increase in accomplishment) in the 19 regions from 2015 to 2030. We observe that South Asia and Middle East and North Africa show the highest differential increases with respect to their GRP, followed at a distance by Brazil and Sub-Saharan Africa.

Figure 4: Percentage change in factor use costs required to achieve safely managed water and sanitation according to the SDGs (medium population growth and GRP per capita, SSP2 variant) in 19 regions from 2015 to 2030.

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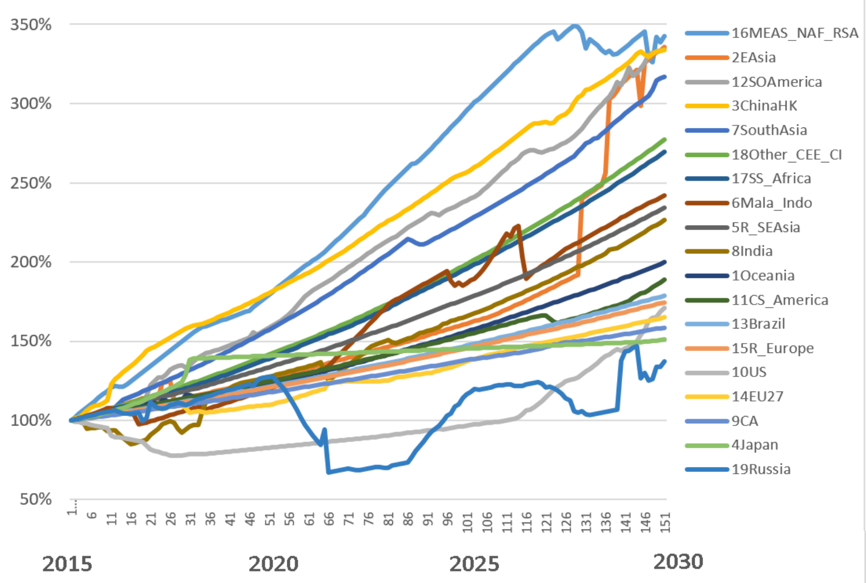

Note: The ordering of the regions from top to bottom follows from highest to lowest end point (in 2030). Source: Modelling results.

Figure 5: Differential change (with safely managed target vs. no increase in accomplishment) in factor use costs in the 13 regions with the highest percentage change from 2015 to 2030 (medium population growth and GRP per capita, SSP2 variant).

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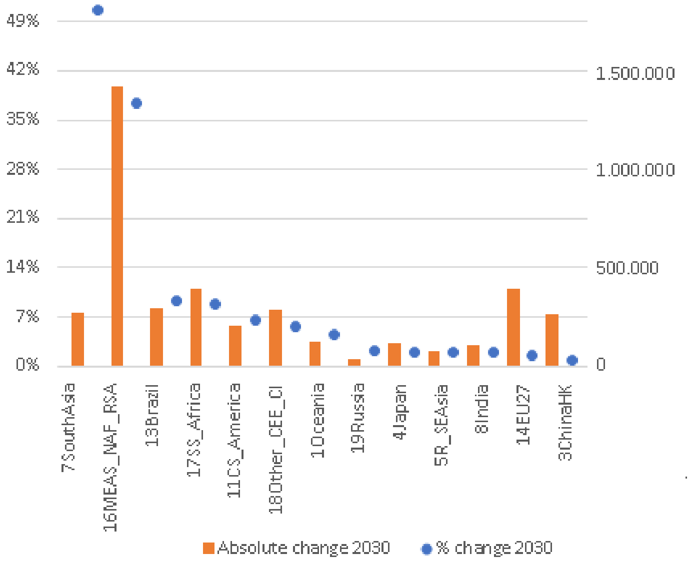

Note: The ordering of the regions from left to right follows the highest percentage change in 2030 with respect to the GRP, as shown in the left axis. The right axis shows the absolute change in US$ million. Source: Modelling results.

4.2. Scarcity rents

In this section, we find that most of the changes in factor earnings do not occur directly in those regions with the highest changes in final demand. We specifically find increasing factor earnings, despite low infrastructure investments, for some affluent regions that already have high levels of water and sanitation coverage. This is explained by how third parties (regions where factor uses are not substantially changed) may get additional earnings from entering into production and trade in the sectors of lowest cost producer regions, increasing factor earnings for those regions that were already producing the technology at a lower price. We may find that the winners from achieving SDG targets are not only those regions that obtain increased coverage, but also those regions where rents are increasingly earned from higher use and scarcity of resources. The main reason for this is that the combination of inputs needed for achieving these goals alter production elsewhere, and hence factor uses. Factors that are fully utilized in a region earn a scarcity rent (**r**). A non-zero rent indicates that the factor is scarce in that region, even if it is not a priced factor.

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To explain this further, Figure S5 shows the projected absolute changes in scarcity rents by region (led in absolute terms by China and EU, followed at a distance by the US, India, Middle East and North Africa, and Japan and Koreas). Similarly, Figure S6 shows the projected absolute changes in scarcity rents by factors. The initial path is stable, which can be explained by the decreasingly important additional capital investments, with some relevant increases in the second half of the period. Figure 6 summarizes the differential change in scarcity rents compared to the Gross Regional Product (GRP) by regions. As shown in Figure 6, the region of Middle East and North Africa obtains the highest increases in scarcity rents as a percentage of its GRP, a result attributable to the increased production in some of the sectors in which this region is a low-cost producer, sectors such as mineral extraction, ferrous metals, petroleum and coal products, chemicals, and rubber and plastic products.

Finally, trade balances indicate the need for further trade in regions that require high increases in water and sanitation coverage. Specifically, these regions will require the importation of relevant inputs, such as chemicals. This is shown in the SM ("Additional results and discussions").

Figure 6: Differential change in scarcity rents (with safely managed target vs. no increase in accomplishment) with respect to GRP by selected (top 12) regions from 2015 to 2030 (medium population growth and GD per capita, SSP2 variant).

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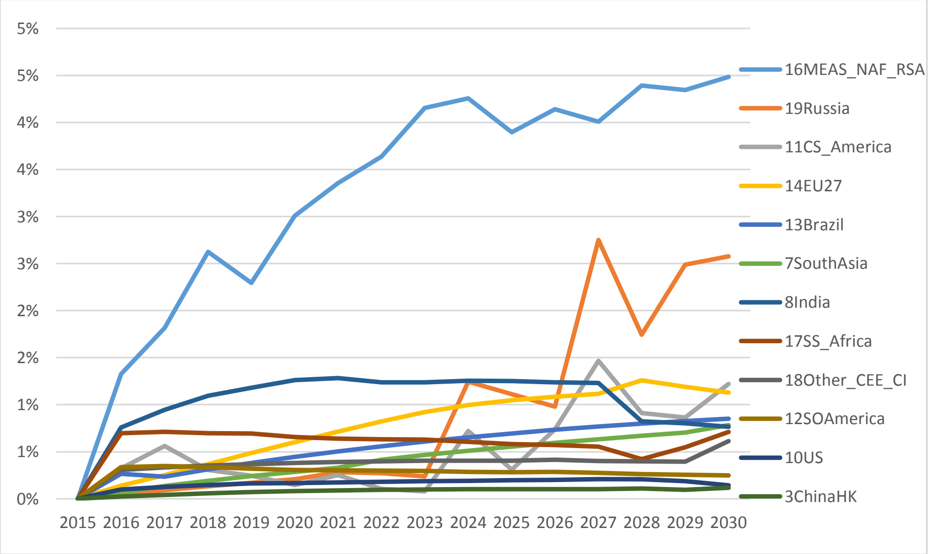

Note: The ordering of the regions from top to bottom follows from highest to lowest end point (in 2030).
Source: Modelling results.

5. Discussions

As we have reviewed, a long thread of literature has very carefully addressed the projected costs and benefits of accomplishing the MDG and SDG targets at the technology detail level (Dobbs et al., 2013; Hutton, 2013; Hutton and Bartram, 2008; Hutton and Chase, 2016; Hutton and Haller, 2004; Hutton and Varughese, 2016; U.N. Water, 2015; Whittington et al., 2007; WHO, 2012; WHO and UN-Water, 2012; World Bank Group and UNICEF, 2017). Previous works offer insightful findings on varying levels of goal accomplishment, investment costs, benefits, and financing gaps. From a methodological perspective, our application of WTM complements these studies by providing detailed information on production, trade balances, prices, factor use, and scarcity rents in an iterative manner with multiple time steps.

Our WTM results on trade balance changes reveal to what extent the regions are specialized (or not) in producing the inputs needed to run water distribution and treatment

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activities. The trade balance results also show how accomplishing the SDGs, with increases in final demand, may typically alter trade relationship with other regions. Realistically, a region may continue importing inputs as long as trade deficits do not hamper the economy.

Going back to our research question, we find the SDG goals physically achievable globally. In terms of monetary findings, our analyses suggest that the worldwide SDG targets can be achieved with moderate costs relative to the total global GDP, especially in comparison to the high estimated cost of inaction (OECD, 2008; WB, 2009). With a full accounting of the costs incurred, including those of increased factor uses, we estimate the yearly global costs of meeting the SDG targets at slightly above US$100 billion, adding up to US1.5 trillion (in 2015 prices) in factor use for the period of 2015-2030. The result is within an order of magnitude of the most comparable work (Hutton and Varughese, 2016), which indicated a total figure of US$3 trillion for the same period.

In this work, production and trade move in line with minimizing global costs. Regions with increasing coverage do increase factor uses, but not to the same extent: some regions, such as South America, notably increase factor use costs along with coverage, but Sub-Saharan Africa, which has the highest increase in coverage, does not have as large an increase in factor uses and barely incurs scarcity rents.

We emphasize our findings on scarcity rents because, while the global economy is growing by most measures (population, resource extraction, production, consumption, etc.), the planet's geophysical resource base does not expand, and its ability to absorb wastes is already being tested (Duchin, 2015).

Our second emphasis is on interregional trade globally and how it is impacted by meeting SDG targets. Within interregional trade, geographic regions at different stages of economic development and material standards of living connect to the material base that is composed of factors of production, including includes water, land, labor, mineral resources, etc. (Hubacek et al., 2016).

The water treatment sectors rely substantially on importable inputs from sectors in which many developed countries are competitive, including coal, petroleum, coal products, chemicals (e.g. U.S., E.U., Japan, also Brazil, Middle East and North Africa), machinery and equipment (China and E.U.), manufactures (e.g. China, India, Brazil, and E.U.), electricity (Russia) and Financial services (U.S.).

The new and replacement capital investments require substantial increases in the construction sector, which subsequently requires inputs of ferrous metals and minerals, business services (in which e.g. E.U. is competitive), machinery and equipment, transport,

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and wood (in which Canada is the low-cost producer). Following the construction sector, the investments require significant outputs from the sectors of machinery and equipment, transport (in which several developed regions are competitive), electronic equipment (in which it is Asian countries are competitive); metals, manufactures and the aforementioned services.

The U.S. and the E.U. showcase the fact that more production, exports, and uses of resources can be triggered in a region by changes in other regions, resulting, in this case, in the development of water treatment sectors in many developing regions. Increases in certain sectors of production are necessary to build up the water purification sector, which in turn increases production in the former sector. In the case of the E.U., we find additional rents on medium quality water, as well as other resources, such as minerals and timber. In the case of U.S., we see increased rents on energy factors and capital due to the exhaustion of current endowments. Even more noticeably, North Africa and the Middle East is the region with the most important differential changes (safety managed water and sanitation vs. no target accomplishment), and it also provides some of the inputs and gains profits from rents in fossil fuels.

6. Conclusions

In this article, we demonstrate uses of WTM/RCOT for waste management and recycling analysis and modelled the conditions and outcomes of SDG targets on water and sanitation. We increase the “granularity” of the data in the model to explicitly express waste inputs, waste outputs, and factor uses by the final demand. We represent returns or byproducts as raw materials (factors) as well as commodities using **F** and **A** matrices. We introduce data and methods to account for cumulative new investments, using **k** vectors, and capital replacement, using **R** matrices. We conclude that, confirming some existing studies, our analyses not only find physically feasible to satisfy the SDG goals regarding safe water and sanitation by 2030, but also find moderate costs associated with meeting them across the world.

The WTM enables a parsimonious representation of the world economy with few equations, variables, and parameters to facilitate instructive interpretations of a wide range of scenarios. Our main motivation in using the WTM is not to replicate the existing production and trade patterns, but to extract fruitful lessons from them. Accordingly, despite the very important role of constraints in providing more realistic baselines, the baseline solution does not reproduce results identical to the raw data on purpose, even though we find the solutions to be consistent e.g. in terms of the share of the output of a technology in a region in the total of the output of the region, or in the total output of that technology in the world (See Table S2). As expected, simulated trade volumes are larger

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than the raw data since a more efficient world economy is assumed with the optimization of factor utilizations.

We observe that the model captures the comparative advantage across the world regions, some of which are favored in terms of production and trade due to them being low-cost producers with larger factor endowments that are necessary for such operations. As part of our parsimonious approach to modeling, we are not interested in covering all complexities and exceptions, such as the inefficiencies, arbitrary political systems and decisions, which condition economics temporally but not consistently and logically. For example, in our modeling effort the role of financial aspects is basically not present, nor aspects such as the relation of trade deficits of the US with being the dollar the predominant reserve currency.

For future studies, we plan to update our analyses to evaluate the accomplishment of other SDGs to address more comprehensive development goals worldwide. The compilation of the database has been a long-lasting process with multiple iterations, continually improving the realism of the baseline runs. Nevertheless, we further plan to increase the "granularity" of the data in the WTM, so that more waste inputs, outputs, and sectors are explicitly expressed. In addition, we would like to integrate further waste treatment and recycling technologies, founded on process-based information in the engineering literature to increase the precision and accuracy of modelling. These further efforts would narrow the gap between the questions of between theoretical feasibility and actual accomplishment. Similarly, we find that there is room for improving the representation of dynamics within the WTM/RCOT, to solve several periods within the same run, considering further aspects such as planned capacity expansion, also for the evolution of more sectors and of endowments. This work successfully incorporated relevant parts of household consumption and its ramifications in the world economy. Further efforts are needed in future work to include important and relevant aspects such as emissions from the gasoline-based vehicles used by households.

Commented [ND3]: Move to discussions?

Finally, future WTM based studies can consider additional benefits from meeting SDG goals by incorporating savings in healthcare costs and contributions to the labor endowments.

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Duchin. We also acknowledge valuable feedback received by the team involved. Any errors are the responsibility of the authors.

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