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Development of a modelling framework to analyze the interrelations between the water, energy and food systems in the Zambezi River Basin

Raphael Payet-Burin and Kenneth Strzepek

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About the project

Southern Africa –Towards Inclusive Economic Development (SA-TIED)

SA-TIED is a unique collaboration between local and international research institutes and the government of South Africa. Its primary goal is to improve the interface between research and policy by producing cutting-edge research for inclusive growth and economic transformation in the southern African region. It is hoped that the SA-TIED programme will lead to greater institutional and individual capacities, improve database management and data analysis, and provide research outputs that assist in the formulation of evidence-based economic policy.

The collaboration is between the United Nations University World Institute for Development Economics Research (UNU-WIDER), the National Treasury of South Africa, the International Food Policy Research Institute (IFPRI), the Department of Monitoring, Planning, and Evaluation, the Department of Trade and Industry, South African Revenue Services, Trade and Industrial Policy Strategies, and other universities and institutes. It is funded by the National Treasury of South Africa, the Department of Trade and Industry of South Africa, the Delegation of the European Union to South Africa, IFPRI, and UNU-WIDER through the Institute's contributions from Finland, Sweden, and the United Kingdom to its research programme.

Corresponding author:

Towards Inclusive Economic Development in Southern Africa

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ABSTRACT

Analyses for water infrastructure investment planning must consider the interdependencies of local and regional water, energy, food, and environmental systems. This highly complex decision problem requires decision support tools to objectively determine the multi-sector economic value of investments while accurately modelling the competition among the sectors for water, land, labour, and capital resources. We employ an open-source hydroeconomic optimization model, What-if, which represents the water, agriculture, and power systems in a holistic framework. We apply the methodology to the Zambezi River Basin, a major African basin shared by eight countries, the regional agriculture system of southern Africa (SADC), and the Southern African Power Pool. We show that the value of the hydropower development plan is sensitive to future fuel prices, carbon pricing policies, the capital cost of solar technologies, and climate change. Similarly, we show that the value of the irrigation development plan is sensitive to the evolution of crop yields, world market crop prices and climate change. Additionally, renewables might significantly impact the power market, but this will have little effect on the agriculture system in the Zambezi River Basin. Trade-offs between agriculture, hydropower and ecosystems are limited under the current climate. But under dry climate change scenarios, prioritizing the hydropower production can generate mild adaption benefits for the power system but results in very large losses for irrigated agriculture while rainfed agriculture and ecosystems also suffers.

Keywords: Hydroeconomic modelling, water resources, investments, Water-Energy-Food-Nexus.

1 INTRODUCTION

When evaluating policies and investments, decision-makers need to be aware of the interrelations between the water, energy and agriculture sector, the so-called "water-energy-food nexus" (Albrecht et al., 2018; Bazilian et al., 2011; Rising, 2020). Ignoring some interrelations might lead to biased assessments, while considering them could indicate co-benefits between sectors (Smajgl et al., 2016). Three challenges are: (1) to define which are the important inter-relations to consider for a specific problem; (2) to confirm what are the relevant spatial and temporal scales; and (3) to find the corresponding data. Various studies analyse the nexus from different perspectives: Payet-Burin (2018) investigates cooling constraints of thermal power, Khan et al. (2017) investigate interrelations between the water and energy sector, and Hamidov & Helming (2020) review the nexus around irrigated agriculture. Recently developed modelling tools combine features from the three sectors and are applied at different scales (Calvin et al., 2019; Howells et al., 2013; Kahil et al., 2018; Kraucunas et al., 2015; Payet-Burin, 2019; Rising, 2020; Vinca et al., 2020).

The International *Model* for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model (Robinson et al., 2015) was developed by the International Food Policy Research Institute and supports analysis of long-term challenges and opportunities for food, agriculture, and natural resources at global and regional scales. Currently it has a simple representation of water constraints and does not integrate climate change scenarios. Considering the interrelations of the food system with the water and energy sector, and the increasing pressure of climate change, the concern is that representing solely the food system might lead to biased analyses, and thus the mid-term objective is to link the model to a water resource model (e.g. Burek et al., 2020). In this study we use the WHAT-IF nexus model (Payet-Burin et al., 2019) applied to the Zambezi River Basin to gain some insights on that concern.

The objective of the study is to assess how the representation of the water, power, and agriculture/land systems affects modelling results of the agriculture/land system, and establish what are potential implications for the IMPACT model.

The study is organized as follows: Section 2 presents the WHAT-IF and IMPACT models. Section 3 introduces the Zambezi River Basin, and the data assimilated by the WHATIF model to represent the water-energy-food nexus. In Section 4, Results and discussion, firstly the model is validated against other studies; secondly, the impact of different representations of renewable energies is evaluated. The Conclusion section summarizes the findings and gives recommendations for representing water constraints in the IMPACT model.

2 THE WHAT-IF AND IMPACT MODELS

WHAT-IF (Payet-Burin et al., 2019) is a hydroeconomic optimization model where the water, agriculture and power systems are represented within a holistic framework. All management decisions regarding water (e.g. storage, allocation), agriculture (e.g. area, crop, trade), and power (e.g. production, transfer, capacity investments) are optimized in order to maximize total welfare economic surplus. The model is based on a perfect foresight and perfect cooperation framework. This means that trade-offs are internally solved, and that one sector might forgo benefits to another in order to generate more benefits at the Basin level. Also, future conditions are known to the optimization framework, which leads to anticipation of wet and dry years.

In WHAT-IF the main link between the energy and agriculture sectors represented in the model is the use of water by hydropower production and irrigated agriculture (Figure 1). Climate change impacts the hydrology, which in turn impacts the water resource and agriculture. Potential yields are an exogenous factor and are affected by hydrological conditions and water allocation using the yield water response function from FAO 56 (Doorenbos & Kassam, 1979). Crop demand, own-price elasticity, available land, and world market prices also are exogenous factors. Trade of crops between crop markets is solved by the economic optimization framework based on transport costs the demand and supply of crops.

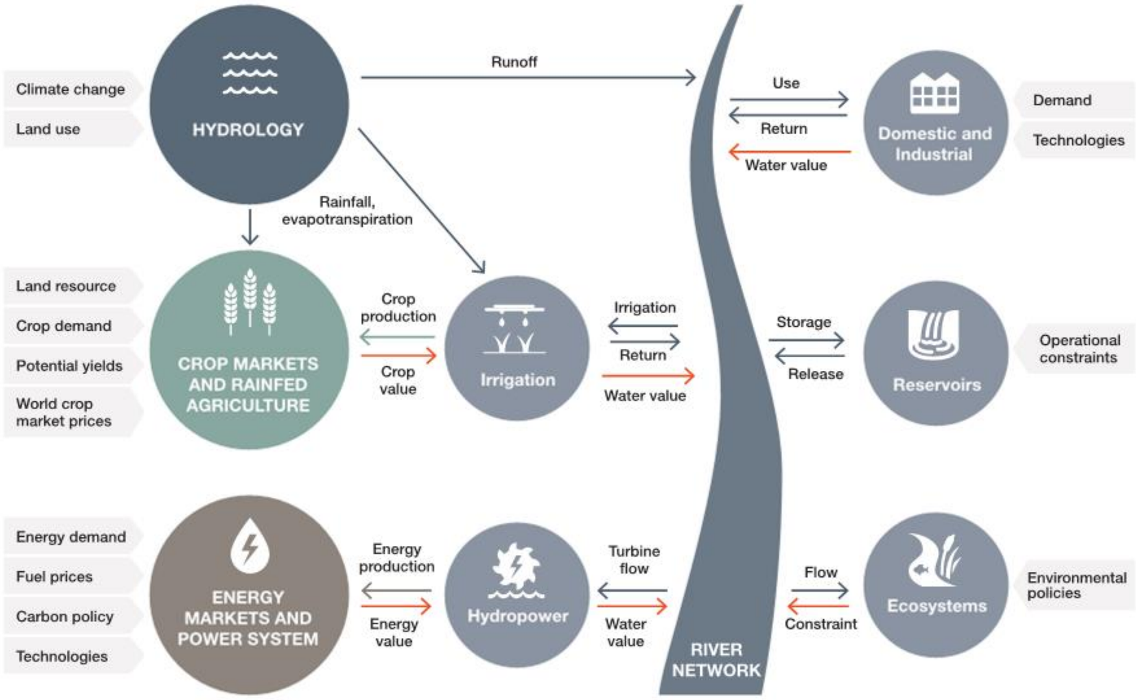

Figure 1: Conceptual representation of interrelations in the WHAT-IF model. The circles represent modules, arrows represent feed-back loops, and grey tags represent exogenous factors. All flows are holistically solved in order to maximize welfare economic surplus.

The IMPACT model contains the following features that are not in WHAT-IF:

- a dynamic feed-back loop between yield and crop price, land price, and fertilizer use;
- different types of crop demand (e.g. urban, rural, livestock);
- world market crop prices, which are the result of the global market trade equilibrium; and
- a global dataset covering the world.

The WHAT-IF model contains the following features that are not in IMPACT:

- representation of hydrology and water infrastructure at catchment scale;
- representation of other sectors using water (e.g. energy, ecosystems);
- representation of multiple harvests per year for crops; and
- an optimization framework performing trade-offs between the different sectors.

3 STUDY CASE AND DATA

3.1 Zambezi River Basin

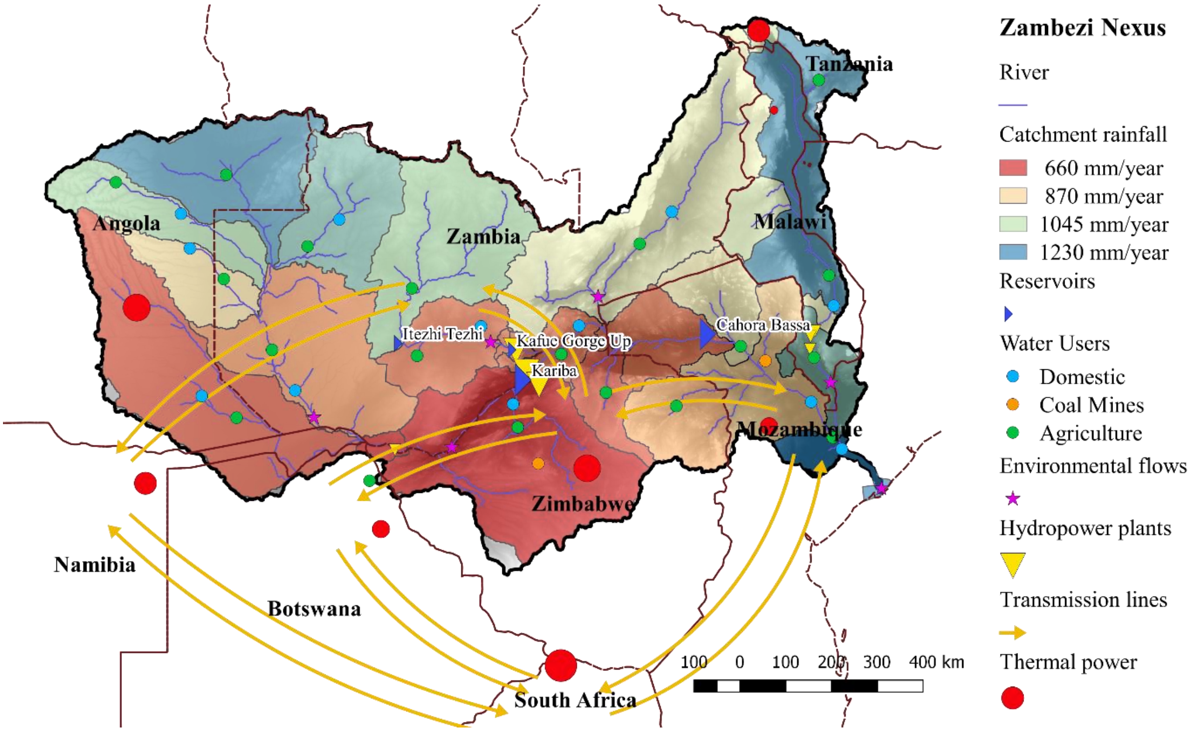

Figure 2: Conceptual representation of the Zambezi River Basin in the WHAT-IF model.

The Zambezi River Basin sustains the basic needs of more than 40 million people in eight riparian countries (Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe). The river is an essential resource, supporting agriculture, hydropower, water supply and sanitation, industries, mining, fisheries, tourism, navigation and ecosystems. The relevant population is expected to grow to 70 million by 2050, which will increase the pressure on the water, energy, and food resources (SADC et al., 2015). The conceptual representation of the river basin in the WHAT-IF model is presented in Figure 2 (some aspects are not represented, such as crop markets).

3.2 Data input

The main WHAT-IF modelling set-up for the Zambezi River Basin is described in Payet-Burin et al. (2019). The main data sources are summarized in Table 1, including some updated data when more recent information was available.

The harvested area data (see Table 2) shows differences between the IMPACT, Spatial Production Allocation Model (SPAM), and Multi-Sector Investment Opportunity Assessment (MSIOA) study (World Bank, 2010) data. Regarding irrigated agriculture in the Zambezi, the MSIOA study should have the most reliable data as it was specifically collected for the Zambezi River Basin, while SPAM and IMPACT are global datasets. Considering the considerable difference between the IMPACT data and the MSIOA data (almost double as much irrigated area in IMPACT compared to MSIOA), two modelling set-ups are compared:

- WHATIF_IMPACT: including all the IMPACT data (demand, price, elasticity, area, yield) for the agriculture system;
- WHATIF: including the IMPACT data only for agriculture markets (demand, price, elasticity), while area and yields are from MSIOA.

Table 1: Main data sources regarding the Zambezi water-energy-food nexus.

Data	Source
Crop demand	FAO (2018); IFPRI (2017)
Crop value	FAO (2018)
Cultivated area	OECD & FAO (2017; World Bank (2010)
Yields and Calendar	OECD & FAO (2017)
Crop calendar	FAO (n.d.); World Bank (2010)
Energy demand	SAPP (2015); Taliotis et al. (2016)
Transmission lines	Taliotis et al. (2016)
Power technologies characteristics	Centre for Environmental Rights, (2017); IRENA (2013); Knorr et al. (2016); Taliotis et al. (2016)
Reservoir and hydropower plants	World Bank (2010)
Hydrology	Baker et al. (2014); Cervigni et al. (2015); World Bank (2010)
Environmental flows	World Bank (2010)

Table 2: Harvested area per crop in the Zambezi River Basin for different data sources. Note that SPAM data is not for the same reference year, however most differences are not related to this.

Total harvested area (1000 ha/y)	SPAM SSA (2017)		IMPACT (2010)		MSIOA (2010)
	Total	Irrigated	Total	Irrigated	Irrigated
Cassava	448	0	613	1	0
Fruits	2 887	7	235	9	7
Groundnut	755	2	545	19	0
Other	58	2	316	13	14
Potato	452	1	377	6	0
Sorghum	401	14	665	22	0
Soybeans	621	0	107	1	14
Stimulants	72	1	72	29	10
Sugarcane	48	28	120	107	78
Pulses	969	1	970	22	0
Cotton	232	4	521	52	22
Maize	3 887	13	4 115	67	17
Rice	135	24	141	12	30
Vegetables	236	11	188	13	12
Tobacco	289	24			7
Wheat	64	33	46	41	41
Total	**11 556**	**166**	**9 031**	**413**	**252**

In the IMPACT model there is only one possible crop calendar (growing seasons) per crop and food production unit (crossing of country and basin). Hence, the model doesn't allow the simultaneous representation of winter and summer crops, and the growing season of crops is assumed to be either winter or summer. This leads the model to grow some rainfed crops (e.g. maize) during winter, which is not realistic as winter is the dry season and without irrigation crops most likely die. Hence, the crop calendars of IMPACT were not used in WHAT-IF.

3.3 Climate and hydrology

The historic climate and hydrologic data comes from the World Bank (2010) Multi-Sector Investment Opportunities Analysis. While this paper does not address climate change, it does report the projected climate changes over the Zambezi Basin developed for the World Bank study on *Enhancing the climate resilience of Africa's infrastructure: The power and water sectors* (Cervigni et al, 2015). On average, climate change scenarios point towards a decrease in average precipitation, with high variability among scenarios (Figure 3). As a result, a similar trend is observed for runoff, with the climate scenarios varying between -40% and +10% runoff on average over the period 2010–2050. As all climate projections point towards an increase of temperature, the average potential evapotranspiration is found to increase for all scenarios. As seen in Figure 3, the range of climate-impacted projected time series for precipitation, evapotranspiration and runoff are presented in comparison to the historical time series data.

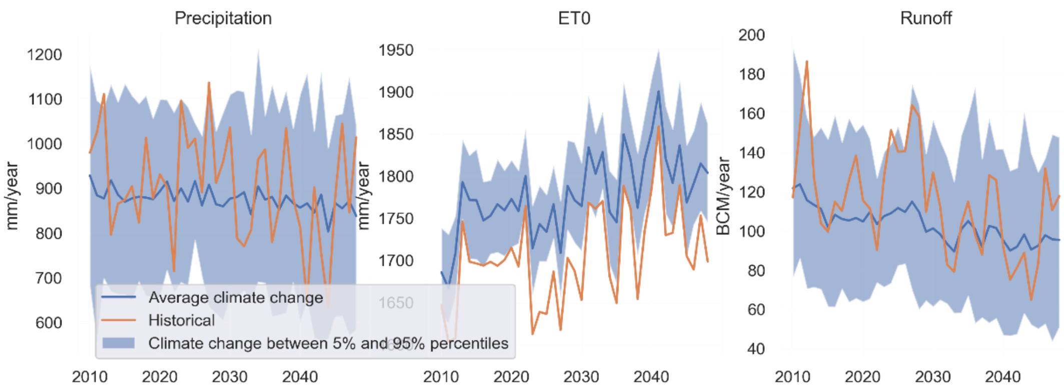

Figure 3: Climate change projections for the Zambezi River Basin. The historical time series is a repeat of the observed hydrology between 1960 and 2000.

4 RESULTS AND DISCUSSION

4.1 Validation of the model

Two set-ups of the model are evaluated. WHATIF integrates uses only IMPACT data for the crop markets, while yield, crop calendar and area are from (Payet-Burin et al., 2019) with main sources from (World Bank, 2010) and (FAO, 2018); WHATIF_IMPACT uses all agricultural data from IMPACT, except crop calendar information. Modelled water balance is compared with other studies (Table 3), and find similar numbers are found for the principal water uses. As the IMPACT data assumes larger irrigated area (Table 2), the resulting irrigation consumption is significantly higher (Table 3, Table 4) than the one found by other studies (around +70 % for WHATIF_IMPACT compared to WHATIF). This difference could impact results when looking at climate change impacts and trade-offs with other sectors.

Table 3: The model water balance compared with other studies (Mm^3/y).

	WHATIF	WHATIF_ IMPACT	World Bank (2010)	Tilmant et al. (2012)	Beilfuss, (2012)	Euroconsult and Mott MacDonald, (2008)
Runoff	115 196	115 196	107 000**		110 732	103 224
Domestic and Industrial consumption	772	772	797			344
Agricultural consumption	3 167	5 344	3 234			1 478
Net reservoir evaporation*	9 778	9 767	8 000	7 800	12 181	16 989

Notes

*Some studies do not report whether this includes the effect of rainfall on reservoirs.

**This is not the value in the report due to a reporting error, but the modelling result.

Table 4: Irrigation consumption per country (Mm^3/y).

	MSIOA	WHATIF	WHATIF_IMPACT
Angola	75	46	46
Malawi	494	547	1 133
Mozambique	134	118	613
Tanzania	154	175	110
Zambia	879	1 381	1 983
Zimbabwe	1 496	901	1 460
Total	**3 234**	**3 167**	**5 344**

The modelled crop production is compared to FAOStats (FAO, 2018) and IMPACT data, while the general trends are reproduced, some differences appear for some crops (Table 5).

Table 5: Crop production per crop (1000t/y).

Description	FAO*	WHATIF	IMPACT	WHATIF_IMPACT
Fruits	817	280	2 149	555
Cereals	787	1 183	610	539
Pulses	900	628	589	419
Stimulants	82	16	101	31
Cassava	7 841	7 547	5 860	5 097
Cotton	-	84	459	174
Oilseeds	943	549	457	375
Maize	6 449	5 905	4 924	5 132
Roots	3 283	3 889	3 620	3 427
Tobacco	314	148	331	246
Rice	262	299	224	101
Sugarcane	8 467	8 169	8 265	8 817
Vegetables	686	1 113	1 069	874

Note

*FAO data is downscaled from countries to the Zambezi River Basin, assuming the production is proportional to population distribution.

The differences between the two modelling set-ups for the agriculture system do not seem to impact the modelled hydropower production, which is comparable to the MSIOA study (World Bank, 2010) in both cases (Table 6).

Table 6: Hydropower production per hydropower plant (Gwh/y).

	MSIOA	WHATIF	WHATIF_IMPACT
Cahora Bassa	13 535	11 214	11 032
Kafue Gorge Up	6 785	7 343	7 655
Kapichira	520	499	499
Kariba N	3 834	4 491	4 292
Kariba S	3 834	3 025	3 052
Nkula	1 017	932	929
Tedzani	722	677	677
Victoria		851	851
Total	30 247	29 034	28 988

4.2 The impact of renewable energies

In the future, renewable energy could play a crucial role in the South African Power Pool, as up to 80% of new capacity investments between 2010 and 2030 could be from various renewable sources (IRENA, 2013). This could, in turn, change how hydropower is used, as it could shift from supplying base load to serving as a battery to compensate irregular renewables. This might in the end modify the temporal trade-offs between irrigation and hydropower.

One challenge when modelling renewable energies is to find the resolution of the temporal scale at which intermittency constraints are correctly represented. A common way of tackling this in models that are at a yearly or a monthly time scale is to further divide the time steps into "load segments" (or "time slices") that represent different demands for power (e.g. base, peak) and different availabilities of renewables.

This section investigates (1) how the definition of time slices impacts the modelled development of renewables; (2) how this impacts the hydropower sector; and (3) how the development of renewables might impact trade-offs between irrigation and hydropower. Three load-segment definitions are evaluated (Table 7):

- Noseg: Only the monthly power demand is considered, and capacity factors for renewables are based on average capacity factor over the year.
- Base: The monthly power demand is divided into three load segments: day, peak (evening) and night. The average capacity factor of renewables over the segments is considered.
- Detailed: In addition to the three load segments, two levels of availability (low and high) are considered for each renewable energy, assuming there is no correlation between the solar and wind.

The data used to compute the capacity factors are presented in the Appendix, based on Centre for Environmental Rights (2017), Knorr et al. (2016) and IRENA (2013). Two scenarios regarding a carbon tax are also considered: no carbon tax, and a USD 50 /t-CO_2-eq tax, which represent different levels of investment in renewable energies.

Table 7: Load segments definitions.

Represent-ation	Load segment	Share of month (%)	Share of monthly demand (%)	Solar capacity factor (%)	Wind capacity factor (%)
Noseg	month	100	100	23	38
Base	day	50	53	45	30
	peak	13	14	0	45
	night	38	33	0	38
Detailed	day_hs_hw	13	13	65	40
	day_hs_lw	13	13	65	20
	day_ls_hw	13	13	25	40
	day_ls_lw	13	13	25	20
	peak_hw	6	7	0	60
	peak_lw	6	7	0	30
	night_hw	19	16	0	50
	night_lw	19	16	0	25

Note:

In the segment name for the detailed slice representation, l stands for low, h for high, w for wind and s for sun; e.g. _ls_hw stands for low sun and high wind availability.

Solar power has the disadvantage of not producing energy during the (evening) peak hour. Hence, representing a single monthly demand (Noseg) leads to higher solar production (Table 8), as it ignores that "handicap" of solar power. Considering two levels of renewable availability for each time slice (Detailed) reduces investments in renewable capacity, as it increases intermittency constraints. The carbon tax has a higher impact on the investments in renewable energies as the definition of load segments, but the sub-mentioned trends are also present. Representing more load segments leads to higher value of hydropower production. This is particularly visible under the carbon tax scenario, where the share of renewables is higher: the Detailed representation leads to a value of hydropower 20% higher than the Base representation for the same level of production. There are two effects: (1) more intermittency leads to higher capacity investments needs and hence a higher average power price; and (2) when representing more load segments, flexible hydropower production can capture higher value energy demand. However, run-of-river hydropower plants already producing at full capacity only gain from an increase in the average power price value, as they cannot adapt their production.

Table 8: Impact of the time slice definition on the power market.

Carbon tax	None			USD 50 /t-CO_2eq		
Representation of time slices	Noseg	Base	Detailed	Noseg	Base	Detailed
Hydropower (%)	54	53	53	55	56	56
Wind (%)	19	23	16	27	31	29
Solar (%)	10	2	1	17	12	11
Thermal (%)	18	22	30	0	1	5
Average power price (USD/MWh)	41	43	44	49	51	60
Value of hydropower production (million USD/y)	2 200	2 430	2 470	2 870	3 140	3 770

Note

The share of hydropower, wind, solar and thermal power is the total modelled share over the Zambezi Countries over the period 2010–2050.

5 CONCLUSIONS

The WHAT-IF model was applied to the Zambezi River Basin to assess the water, energy and agriculture system and their interrelations. Based on this analysis, recommendations are formulated for including water constraints in the IMPACT model.

The definition of load segments affects which renewables are developed. However, other factors might be even more important, such as CO_2 taxes. Renewables might significantly impact the power market, but this will have little effect on the agriculture system in the Zambezi River Basin.

Trade-offs between agriculture, hydropower and ecosystems are limited under the current climate. Prioritizing the agriculture system leads to almost no change with the balanced economic management. In contrast, prioritizing the hydropower production can generate very important losses for irrigated agriculture and generate mild benefits for the power system. Enforcing more ecosystem conservation policies would principally affect hydropower production but could also affect irrigated agriculture under the driest climate change scenarios.

The most important task for the IMPACT model is to consider climate impacts on rainfed crops. To consider water constraints on rainfed crops it is important to improve the data regarding crop calendars and enable the representation of multiple harvests per year. It is important to consider the inter-annual variability of hydrological parameters, which considerably affect water constraints. Irrigated agriculture might be limited by surface water constraints only in the driest years. In the case of the Zambezi, representing surface water constraints for irrigated agriculture by ignoring the other sectors would lead to only little bias in the analysis, despite the potential evolution of the hydropower management

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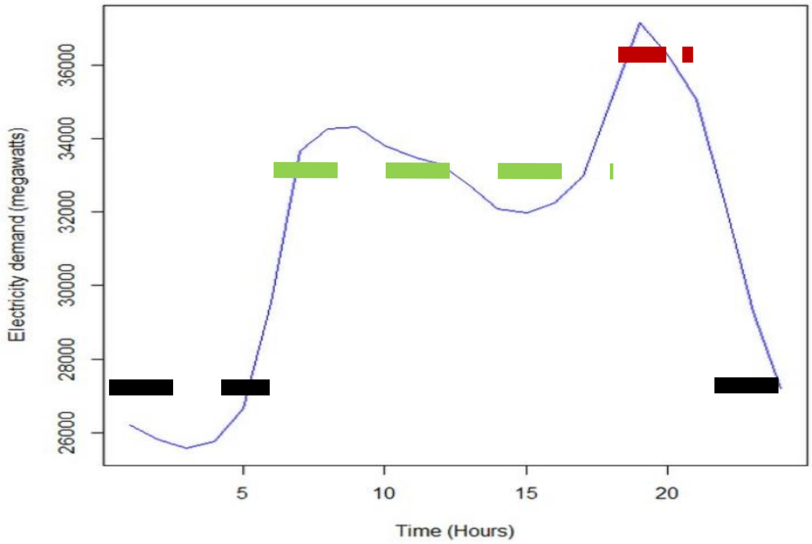
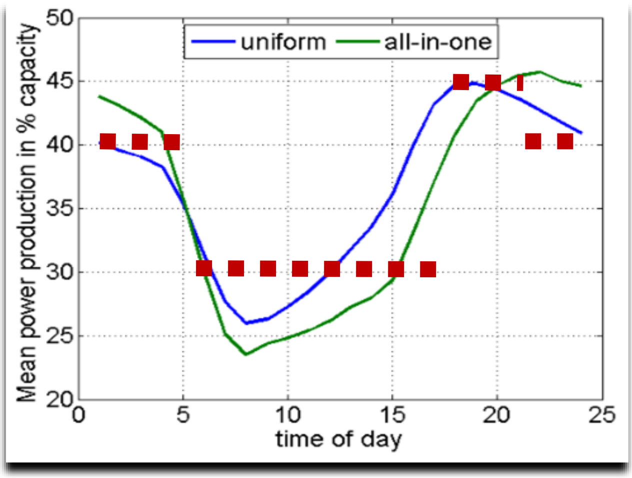
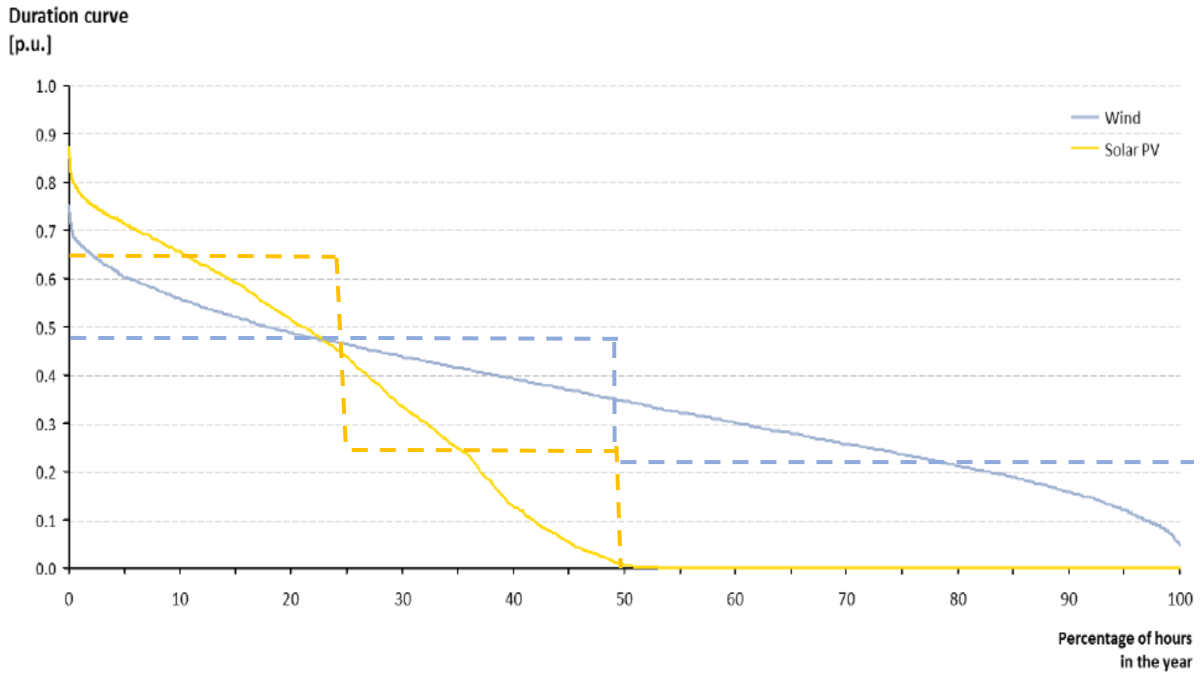
APPENDIX: LOAD SEGMENTS AND CAPACITY FACTORS OF RENEWABLES







Time Slice	Solar Average	Solar High	Solar Low	Wind Average	Wind High	Wind Low
Day	45%	65%	25%	30%	40%	20%
Peak (evening)	0	0	0	45%	60%	30%
Night	0	0	0	38%	25%	50%
Average	**23%**			**35%**		

About the authors

Raphael Payet-Burin is Ph.D. student (industrial) in partnership with COWI, the Technical University of Denmark (DTU) and the Massachusetts Institute of Technology (MIT). Ken Strzepek is a Research Scientist at the Joint Program on the Science and Policy of Global Change, MIT, Cambridge, MA.

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
A world free of hunger and malnutrition
1201 Eye Street, NW | Washington, DC 20005-3915 USA
T: +1.202.862.5600 | F: +1.202.862.5606
Email: ifpri@cgiar.org | www.ifpri.org

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