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Bioenergy sources from agricultural crop residues

An assessment at regional level in the Senegal River Basin

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Contents

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Abstract

In Western Africa access to energy for small and medium-sized enterprises in rural areas is difficult, inconsistent and often expensive, however possible solutions and support can be found in less explored resources such as agricultural product residuals and agro-industrial waste. Demand for woodfuel (mainly fuelwood in rural areas and charcoal in urban areas) is projected to increase steadily creating a worrying situation because of the resulting net increase in forest degradation, specifically in the Upper Senegal river basin.

The overall objective of this analysis is to evaluate the availability of agricultural residues that could potentially be converted into energy production to contribute to energy demand satisfaction. The specific objectives of this analysis is to assess how local agricultural crop residues may potentially sustain local energy demand from several sectors, but specifically from household energy demand and irrigation energy demand for water pumping and movement. This assessment requires the consideration of different objectives that can be contrasting and difficult to be balanced. In doing so, we need to deal with the following issues: (1) multiple crop specific residues productivity (2) multiple crop specific residues energy capacity (2) limited resources for crop management improvement (such as fertilizers and irrigation) and (3) variable household demands. To that purpose a Multi Objective Optimization (MOO) tool integrating regional data and the energetic model was developed. The aim of such a system is to assess the bioenergy productivity in the Senegal river basin in a WEFE Nexus context. More specifically the bioenergy model is aimed to be able to take into account different objectives (Nexus objectives or objectives linked with different Nexus components), usually contrasting objective and to identify optimal solutions allowing end users for the identification of the most suited trad off across the sectors.

The technical analysis has shown that there is indeed an important potential to use these resources to generate electricity without impacting the other sectors involved. The assessment estimated the total production of residues available for transformation in about 7 M of tons in the Senegal river basin for the year 2016. Assuming the efficient exploitation of these residues to supply an ideal 600 kW cogeneration plant, the resulting energy efficiency potential for 2016 in the Senegal River basin was estimated approximately in 4.4 MWh per year. Concerning spatial distribution of energy availability this is more concentrated in the Kayes area in Mali while for other regions it is much more regionally distributed along the main valley. The spatial identification is important as allows to identify energy strategy that can be realistically applied in rural areas, without requiring important movement, transport and storage of residues for such small installations.

In addition to this preliminary assessment, an analysis focused on the inclusion of WEFE Nexus concept has been developed. An analysis has been implemented by focusing on 2 objectives at a time for optimization (maximization and/or minimization) while using other indicators as constraints. Results point out that a wide range of "optimal" solution is produced and even with very different crop land allocation and optimization scenarios, the new optimal quantity of energy that can potentially be produced is increased of about 25%, if compared with current management. This analysis is an example of how these strategies, combined with other key solutions for energy production (such as PV and Solar, etc.), can be effectively used to improve Senegal river basin to achieve an higher access to electricity level and an higher contribution of bio energy source. With about 7 million of people living in great part in rural areas, exploring such bio energy technology has showed its potential and also it showed the importance of applying WEFE Nexus concept in the assessment, thus allowing to identify higher productivity level but ensuring other important aspects.

1 Introduction

Access to energy services is a priority for sustainable economic development in Africa, particularly in rural areas. Increasing access to reliable, affordable and clean energy resources is a key priority, particularly in sub-Saharan Africa (IRENA, 2019a). In Western Africa access to energy for small and medium-sized enterprises in rural areas is difficult, inconsistent and often expensive, however possible solutions and support can be found in less explored resources such as agricultural product residuals and agro-industrial waste. These residuals and waste can make up an important renewable energy source, as they can be converted into heat and energy to support agriculture processing and farmers. In general, the capability of reuse such products will enable to supply energy to rural areas (maybe not connected with energy grids, or at a more competitive cost), to support the processing of the products itself and overall, the economical sustainability of small farming. Several projects and studies are focusing on this sector to identify which technology can be optimal at this scope (among others (Scarlat and Kougias, 2018; Smith et al., 2015) but an important aspect is also to assess where and how much resources can be realistic available. This may depend, for instance, on how these productions will be affected by climate variability and climate change and which is the benefit to other sectors (reduce of environmental impact such limiting deforestation, loss of soil and erosion of river bank, and reducing greenhouse gas emissions).

Box 1 Agricultural product residuals and agro-industrial waste

In Western Africa access to energy for small and medium-sized enterprises in rural areas is difficult, inconsistent and often expensive, however possible solutions and support can be found in less explored resources such as agricultural product residuals and agro-industrial waste

In West Africa, **electricity access rates range from below 20-35% in Liberia, Sierra Leone, Niger, Burkina Faso and Mauritania, to 40-45% in Mali and Guinea and more than 60% in Senegal**. By considering rural areas, these figures are much lower: 9, 12, less than 1 and 35% for Guinea, Mali, Mauritania and Senegal respectively (World Bank, 2020).

Renewable energy in Western Africa

The West African region has a vast renewable energy potential sufficient to cover unmet power demand and achieve universal access to electricity while supporting the region's transition to a low-carbon growth path. In July 2013 the Authority of Heads of State and Government of the Economic Community of West African States (ECOWAS) adopted the ECOWAS Renewable Energy Policy (EREP); this aims to increase the share of renewable energy in the region's overall electricity mix to 35% in 2020 and 48% in 2030 (to 10% and 19%, respectively, excluding large hydrological power plants). Complementing the EREP, the ECOWAS Energy Efficiency Policy (EEEP) aims at making available 2000 megawatts of power generation capacity through efficiency gains and ultimately, doubling the rate of improvements in energy efficiency (IRENA, 2020)

1.1 Energy sectors and Energy Balance in the Senegal River Basin countries

At the end of 2015, the total energy consumption for the 4 countries of the Senegal River Basin was about 372 000 (tera joule), of which **the share of renewable energies** (including energy consumption from all renewable resources: hydro, solid biofuels, wind, solar, liquid biofuels, biogas, geothermal, marine and waste) is about of 42,7 for Senegal, 32.2% for Mauritania, 61.5% for Mali and 76.3% for Guinea.

According to UN figures for year 2017, the highest total energy supply (that includes the primary production, the import/export exchanges and losses and own uses) are for Senegal and Guinea with respectively about 47 000 and 43 000 GigaWh1, while Mali and Mauritania have 27 000 and 20 000 GigaWh. Looking at the source of such energy supply,it is noted that the quote of energy coming from biofuels and waste is generally high, ranging from 30 to 70% of the total energy supply in all the four countries (see Figure 2 for details) .

[1] Megawatthour = 0.0036 Terajoule

Figure 1. Left: Total Energy consumption as reported by WorldBank Data for the period 2007-2015; Right: Total energy consumption by sector as reported by United Nations, Energy Statistics database.

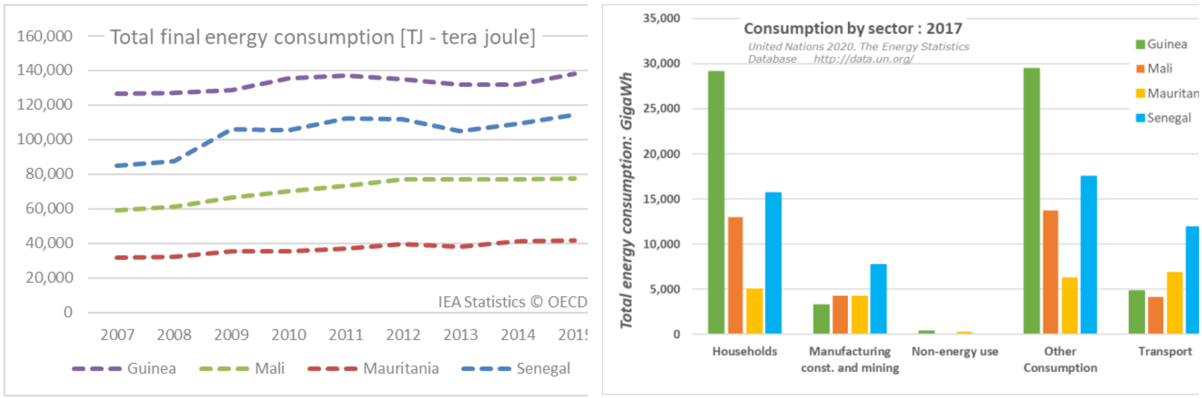
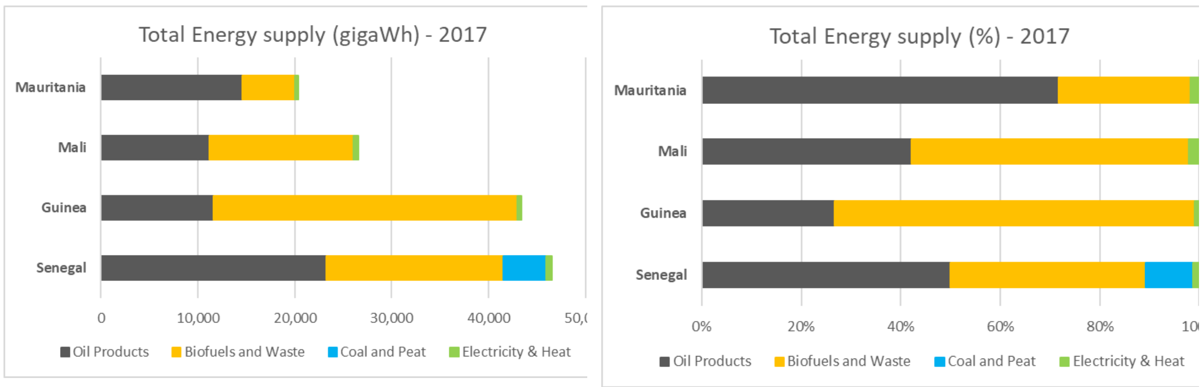


Figure 2. Energy balance: Total Energy Supply (including production, imports, exports) in 2017 in the four countries. Left: energy by commodity as total annual gigawatt/h; Right: energy by commodity as relative percentage.



More specifically:

- Oil product source is dominant in Senegal and Mauritania and the second source in Mali and Guinea
- Bioenergy and waste is the dominant source of energy in Guinea and Mali

Electricity share is much limited in all countries (about 1%).

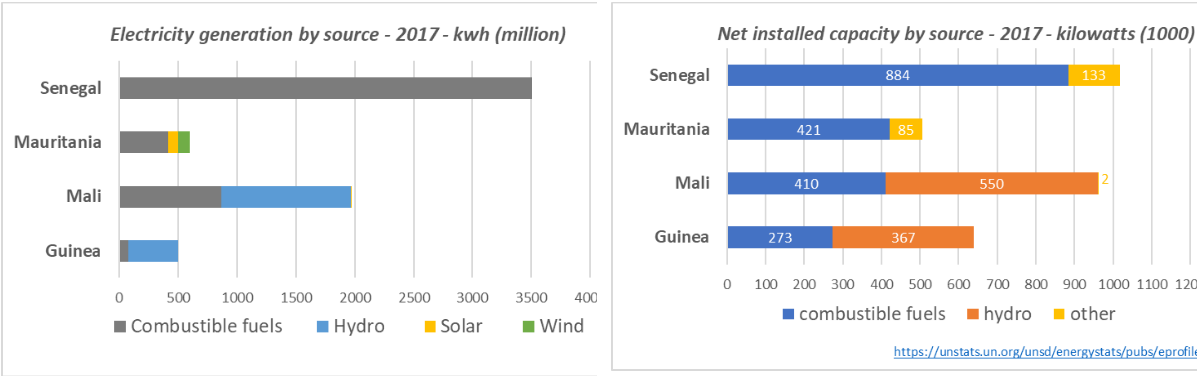
Energy consumptions at country level

Energy consumptions are quite different from energy supply, and are much higher for Guinea and Senegal (at national level) with about 67 000 and 53 000 GigaWh and lower in Mali and Mauritania with 35 000 and 22 000 GWh per year. The main consumer with the highest demand for energy in all the four countries are the households: respectively with a share of 44, 37, 30 and 22 % in Guinea, Mali, Senegal and Mauritania. A detailed repartition of energetic consumption in the 4 countries is available in Table 1 where Energy Balances sheet at National level have been estimated (based on UN Energy statistics). While households demand is generally dominant in the Senegal river basin, Mauritania is an exception where the highest consumption is made for transport.

Looking specifically at the electricity supply, electricity is mainly generated using combustible fuels in Senegal and Mauritania, while hydropower electricity generation is the main source in Mali and Guinea (see

Figure 3). Indeed one important contribution to electricity production in the Senegal River basin is Manantali hydropower plant (a higher part of the energy produced is for Mali, following Senegal and Mauritania). In Mauritania, there are significant shares of electricity produced with solar and wind energy.

Figure 3. Left: Electricity generation by several sources in 2017; and right: Net Installed capacity in thousands of kilowatts. Data elaborated from United Nations Energy Statistics as available at: https://unstats.un.org/unsd/energystats/pubs/eprofiles/



This is reflected in the distribution of the "Net installed capacity" by different sources in the four countries but additionally, this indicator captures the electricity capacity from other sources. For instance, Senegal has a significant capacity provided by other sources (mainly solar).

1.2 The PEC (Politique energetique commune), a strategic document between the four countries belonging to the Senegal River Basin.

A summary extracted from the PEC documentation follows.

Guinee

In 2013 according to the PEC (Politique énergétique commune des pays members, (OMVS, 2014)), Guinee produced 654 GWh of energy. The productive energetic system is based mainly on hydropower accounting for 73,5% and on thermal power (26.5%), while other sustainable renewable energies are negligible.

An important objective set-up in the Strategic planning for energy sector (Programmes du secteur électricité 2014-2030, Guinee- Axe 3) is to reduce dependence on fossil fuels by the development of non-conventional energy sources to replace running thermal equipment.

Demand is expected to growth with an annual rate of 14.5% (2013: 802, 2030: 7993 GWh, (OMVS, 2014)).

Mali

In 2013 according to the PEC (Politique energetique commune des pays members, (OMVS, 2014)), Mali produced 1420 GWh of energy. The productive energetic system is highly dependent on hydropower accounting for 54%, on thermal power (fuel and gas oil) for 31.4%, while renewable energies (some PV systems) are negligible. The rest is imported from Cote d'Ivoire. Demand is expected to growth from 1059 in 2011 to 8862 GWh in 2030 (OMVS, 2014)). Current installed capacity is about 310 MW of which 40% thermal, 60% hydropower. As in most sub-Saharan African countries, biomass (mainly in the form of firewood) provides the bulk of the energy supply: Mali's total primary energy supply in 2014 reached

5.1 million tonnes oil equivalent (Mtoe) out of which 3.6 Mtoe (69%) is from firewood and 7% from

Charcoal 4. The share of other biomass is limited to residues (<0.5 %), mainly from agriculture and forestry. Petroleum products accounted for 1.02 Mtoe (20%) mainly gasoline and diesel for the transport sector. The share of electricity, including imports, is only 3.8% of total energy supply (IRENA, 2019b).

An important objective set-up in the strategic planning for energy sector is the strong penetration of Renewable Energies in general and, in particular, of photovoltaic solar power plants that inject electricity into the interconnected Grid.

Box 2. The PEC in the four riparian countries of the Senegal river

Key points:

GUI: Objective -reducing dependence on fossil fuel by the development of non-conventional energy sources

GUI: Demand is expected to growth with an annual rate of 14.5%

MLI: Demand is expected to growth from 1059 in 2011 to 8862 GWh in 2030

MLI: Objective –fostering the strong penetration of Renewable Energies in general and, in particular, of photovoltaic solar power plants.

MLI: Firewood contribute for 69% for energy supply (2014)

MLI: The share of electricity, including imports, is only 3.8% (IRENA, 2019b).

MAU: SOMELEC energy installed capacity was nearly 159.5 MW (2013)

MAU: Thermal power accounting for 71%

MAU: Significant renewable energy resources: photovoltaic (PV) potential is 2 000-2 300 kilowatt-hours per square metre per year

MAU: Objective - developing appropriate solutions for remote centres and rural areas.

MAU: Electricity demand is growing by 10% per year

MAU: 67% biomass (wood and charcoal), main resource used in the country for electricity production is heavy fuel oil

SEN: energetic system based mainly on thermal power (90%) and hydropower derived by Mali

SEN: access to renewable energy is increased to 17% in 2019

SEN: energy consumption is growing rapidly (+3.6% year)

SEN: Energy consumption for capita in 2017 is reported as 0.3 MWh/capita

Mauritanie

In 2013, SOMELEC energy installed capacity was nearly 159.5 MW, of which 69% supply Nouakchott and by considering also Nouadhibou it reaches 92.5%.

The productive energetic system is mainly based on thermal power accounting for 71% and photovoltaic (3%), while other shares are derived by OMVS agreement (26%, from hydropower: Manantali-Felou) and others (DSPE and SNIM for wind and photovoltaic). Mauritania has significant renewable energy resources. The estimated solar photovoltaic (PV) potential is 2000-2300 kilowatt-hours per square metre per year (kWh/m2/year). (IRENA, 2015).

An important objective set-up in the strategic planning for energy sector is the developing appropriate solutions for remote centres and rural areas.

Electricity demand is growing by 10% per year, led primarily by industry needs and fuelled in part by rising domestic demand. The current installed generation capacity is around 350 megawatts (MW), of which 75% is based on heavy fuel oil (HFO). (IRENA, 2015). Demand is expected to increase from 123 MW in 2010 to 567 MW in 2030.

Annual primary energy consumption in the country was estimated at 4.8 million barrels of oil equivalent (0.7 million tonnes of oil equivalent, or toe) in 2010 (EIA, 2013). Annual consumption per capita is 0.3 toe (GTZ, 2009), or 0.17 toe if traditional biomass is excluded. Mauritania's energy mix comprises approximately 67% biomass (wood and charcoal), followed by petroleum products, which account for the vast majority of commercial energy used in the country. Electricity consumption is increasing by more than 10% per year, yet less than 5% of the rural population has access to electricity. The main resource used in the country for electricity production is heavy fuel oil (HFO), which accounts for 75% of the installed generation capacitytricity (EIA, 2013). Despite Mauritania's largely desert climate, an estimated 67% of the country's primary energy needs are met through the use of traditional biomass (wood and charcoal). Agricultural waste in the country previously totalled just over 500 000 tonnes/year, with a corresponding energy potential of some 3.7 gigawatt-hours (GWh). However, the period between 1991 and 2001 saw a decline in agricultural production. Although agricultural activities have since resumed, the resource potential should be re-evaluated.

Senegal

In 2013 according to the PEC (Politique energetique commune des pays members, (OMVS, 2014)), Senegal produced 3038 GWh of energy. The productive energetic system was based mainly on thermal power accounting for 90% and hydropower derived by hydroelectric centrals of Mali (10%, from Manantali and Felou), while renewable energies are negligible. According to Plan Senegal Emergent (2019-2023) the access to renewable energy is increased to 17% in 2019. Current installed capacity is about 864MW of which 85% thermal, 7% hydropower and 5% is solar. Senegal's per capita energy consumption in 2016 was 0.27 toe, including approximately 230 kWh of electricity. The country's total energy consumption is growing rapidly (+3.6%/year, on average, since 2000). The production capacity of 843 MW installed in 2015 including 489 MW by thermal power plants managed by SENELEC public limited company with majority government. Thanks to the IPPs, the country installed capacity has increased to 1000 MW in 2016 and 1100 MW in 2017. the share of renewable energy in the total power generation capacity will evolve from 10% of hydro, 0,4% of solar PV and 0% of wind in 2015 to 13% of hydro, 13% of solar PV and 8% of wind power in 2020, whilst the total capacity will be multiplied by 2,3 up to 2 GW in the same period.(Saïd Ba, 2018a)

Energy consumption for capita in 2017 is reported as 0.3 MWh/capita (IEA, 2020).

Senegal has actively pursued reform policies in the energy sector (Saïd Ba, 2018b), with a strong focus on promoting renewable energy and a specific plan for Renewable Energies development is in place to address the regional strategy of ECOWAS (Plan d'Actions National des Energies Renouvelables (PANER) (CEREEC, 2015)). The current energy policy is reflected also in the "Lettre de Développement du Secteur de l'Energie (LPDSE 2008)".

PNB-SN II (2014-2017) : National Biogas Program: (ii) make household bio digesters of larger sizes more suitable to Senegalese households; (iii) better understand the importance of agriculture and livestock in the biogas sector; The National Action Plan for Renewable Energies (PANER) defines the targets for REs injected into the grid in 2025 as follows: Power of 440 MW from different sources. The objective of the Government in the sub-sector is to provide sustainable supply of urban and rural households with cooking energy, while ensuring the preservation of forest resources.

Table 1. Energy country balance sheets for 2017. Data elaboration from United Nations Energy Statistics.

Country	Transactions(down)/Commodity(right)	Energy Unit: Terajoules								
		Primary Coal and Peat	*Coal and Peat Products*	*Primary Oil*	*Oil Products*	*Natural Gas*	*Biofuels and Waste*	*Electricity*	*Heat*	*Tota Energ*
SENEGAL	*energy supply*									
	Primary production	0	0	0	0	662	65925	309	513	**6740**
	Imports	15887	0	50760	53910	0	0	1213	0	1217
	Exports	0	0	0	-11347	0	0	0	0	-113
	Others	0	0	5034	-14771	0	0	0	0	-973
	Total energy supply	15887	0	55794	27792	662	65925	1522	513	**1680**
	Transformation	0	0	-55794	21941	-662	-18824	15865	-513	-379
	Losses and own uses	0	0	0	-1237	0	0	-2800	0	-403
	Final consumption									
	Total energy supply + Transformation - Loss	15887	0	0	56529	0	47101	14227	0	**1337**
	Manufacturing const. and mining	15887	0	0	6636	0	1171	4136	0	2783
	Transport	0	0	0	42851	0	0	0	0	4285
	Other Consumption	0	0	0	7042	0	45930	10091	0	6306
	Non-energy use	0	0	0	0	0	0	0	0	0

	Transactions(down)/Commodity(right)	*Primary Coal and Peat*	*Coal and Peat Products*	*Primary Oil*	*Oil Products*	*Natural Gas*	*Biofuels and Waste*	*Electricity*	*Heat*	*Tota Energ*
GUINEA	*energy supply*									
	Primary production	0	0	0	0	3	113017	1539	0	**1145**
	Imports	0	0	0	42914	0	1	0	0	4291
	Exports	0	0	0	0	0	-24	0	0	-24
	Others	0	0	0	-1127	0	0	0	0	-112
	Total energy supply	0	0	0	41787	3	112994	1539	0	**1563**
	Transformation	0	0	0	-13638	0	-10218	4771	0	-190
	Losses and own uses	0	0	0	0	0	0	-676	0	-67
	Final consumption									
	Total energy supply + Transformation - Loss	0	0	0	28235	3	102777	5580	0	**1365**
	Manufacturing const. and mining	0	0	0	8822	0	629	2376	0	1182
	Transport	0	0	0	17262	0	0	0	0	1726
	Other Consumption	0	0	0	745	3	102147	3204	0	1060
	Non-energy use	0	0	0	1407	0	0	0	0	140

	Transactions(down)/Commodity(right)	*Primary Coal and Peat*	*Coal and Peat Products*	*Primary Oil*	*Oil Products*	*Natural Gas*	*Biofuels and Waste*	*Electricity*	*Heat*	*Tota Energ*
MALI	*energy supply*									
	Primary production	0	0	0	0	0	53357	3985	0	**5734**
	Imports	0	0	0	42381	0	4	0	0	4238
	Exports	0	0	0	0	0	-27	-1980	0	-200
	Others	0	0	0	-2073	0	-1	0	0	-207
	Total energy supply	0	0	0	40308	0	53333	2005	0	**9564**
	Transformation	0	0	0	-9332	0	-9567	3114	0	-1578
	Losses and own uses	0	0	0	0	0	0	-288	0	-288
	Final consumption									
	Total energy supply + Transformation - Loss	0	0	0	30976	0	43765	4831	0	**7957**
	Manufacturing const. and mining	0	0	0	12790	0	0	2574	0	1536
	Transport	0	0	0	14901	0	0	0	0	1490
	Other Consumption	0	0	0	3285	0	43765	2257	0	4930
	Non-energy use	0	0	0	0	0	0	0	0	0

	Transactions(down)/Commodity(right)	*Primary Coal and Peat*	*Coal and Peat Products*	*Primary Oil*	*Oil Products*	*Natural Gas*	*Biofuels and Waste*	*Electricity*	*Heat*	*Total Energ*
	energy supply									
M A U R I T A N I A	Primary production	0	0	9995	0	0	19448	659	0	**3010**
	Imports	0	0	0	53143	0	0	666	0	5380
	Exports	0	0	-9995	0	0	0	0	0	-999
	Others	0	0	0	-595	0	0	0	0	-596
	Total energy supply	0	0	0	52548	0	19448	1325	0	**7332**
	Transformation	0	0	0	-6638	0	-5606	2462	0	-978
	Losses and own uses	0	0	0	0	0	0	-665	0	-665
	Final consumption									
	Total energy supply + Transformation - Loss	0	0	0	45910	0	13842	3128	0	**6288**
	Manufacturing const. and mining	0	0	0	14340	0	0	828	0	1516
	Transport	0	0	0	24608	0	0	0	0	2460
	Other Consumption	0	0	0	6206	0	13842	2300	0	2234
	Non-energy use	0	0	0	756	0	0	0	0	756

Source: UNSTATS database: https://unstats.un.org/unsd/energystats/dataPortal/.

2 Agricultural residues potential for bioenergy in the Senegal River Basin

2.1 Context

In view of the above, there is high interest in Western Africa to further develop capacity and diffusion of alternatives to fossil energy sources and thus reducing the carbon footprint, the country's dependence on oil and fossil fuel, reducing the impact on natural resources (wood) and pursue political and economic goals through utilizing under-utilized and domestically available resources. Mauritania pointed out in the PEC the importance, as energetic resource, of agricultural waste and also that an assessment is needed. Energy potentials from agricultural residues and agro-industrial residues could be explored for present and future energy needs. Residue-based biofuels, however, are not automatically environmentally benign nor do they ensure the development of a sustainable energy supply (Kemausuor et al., 2014). Indeed for example crop residues collection may requires additional energy inputs and also the extensive use of such residues can impact nutrient availability and soil fertility is not properly manged (if for example all crop residues are removed from soil).

Demand for woodfuel (mainly fuelwood in rural areas and charcoal in urban areas) is projected to increase steadily and total production was about 26 Mm^3 in 2018 (Figure 4). This increasing production is creating a worrying situation because of the resulting net increase in forest degradation, averaging about 40 000 ha during the period 2001–2018, equivalent to a 16% decrease in tree cover since 2000 for the Upper river basin (Elaboration from Hansen et al., 2013).

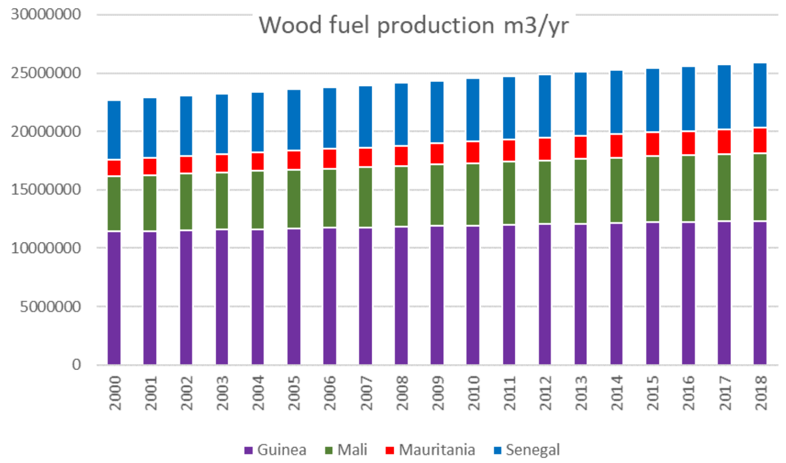
Direct human pressures, linked mainly to population growth, the need for more land to satisfy the demand for food and biomass energy, poverty, and cultivation and livestock methods, are also leading to changes in vegetation cover, loss of interspecies and genetic diversity, and decreased integrity of the wildlife habitat. N addition intensive grazing has led to degradation of natural pasture land (FAO, 2019). The main causes of woodland degradation are unsustainable wood harvesting for timber and woodfuel and the lack of sustainable forest and woodland management.

Box 3 Woodfuel and tree coverage

- Woodfuel demand is increasing rapidly in the region: +14% increase in the 2000-2018 period
- Tree cover is decreasing fast: -16% in the 2001-2018 period

In order to reduce woodfuel usage and hence, reduce the rate of forest degradation, biogas for cooking should be encouraged and implemented with locally produced biogas (Rupf et al., 2015).

Figure 4. Wood fuel total production in the 4 countries of the Senegal River Basin for the period 2000 – 2018 (Increase of about 14% or about 0.78% per year). Source: Faostat (Access 1/Apr/2020).



2.2 Objectives and expected results

Biomass is a renewable energy resource derived from living or recently living organisms that is becoming more and more an important energy source even in developing countries in a context of sustainable energy production (Kemausuor et al., 2014). Western African countries are highly dependent on biomass sources (such as savannah, forest, and agriculture) and currently biomass is intensively used but in low efficient ways, such as firewood and charcoal for cooking and heating. Climate change (CC) and Climate variability (CV) will impact also biomass exacerbating the pressure on this limited resources. In addition the Senegal River Basin region is expected to duplicate its population from 2010 to 2050 and already in 2010, about 83% of people relied on firewood and charcoal for domestic energy services (EREP Policy (ECOWAS/Economic Community of West African States, 2015)).

Biomass could contribute in a certain extent to cope with these challenges enabling energy security and poverty reduction in a sustainable way. The use of agricultural residues to satisfy energy requirements is a potential way to guarantee energy services avoiding common Biofuels issues. Multi-feedstock plants using agricultural residues to produce bioethanol, synthetic natural gas (SNG) and electricity are potential options for energy procurement (Gnansounou et al., 2020). An important aspect to be considered is that this envisaged more efficient biomass conversion in such a region (Senegal River Basin, and more specifically the rural areas) requires a challenged technology transfer and appropriate logistics systems that are implicitly assumed by the study (or in another way left for future feasibility studies).

> Residues conversion and use of such plants can be really supporting for supplying energy to rural population living in remote or not well connected areas.

Currently, about 40% of the population (an estimated 4 million people), living in sparsely populated rural communities, remain unconnected to electricity.

Generally, grid-based electrification to these communities is highly uneconomical (Nerini et al., 2016) and in this cases the use of *distributed generation* is the only possible solution.

A more efficient use of such resources would allow to limit energy demands and at the same time to reduce the pressure on natural resources. The bulk of this new resources need to be derived by residues of agriculture, and not by agricultural products itself as in the case of biofuels: in this sense, this approach should be seen as a way to optimize scrap materials without impacting land use and standard crop productivity.

Renewable energy-based mini-grids to be targeted to rural off-grid communities.

Currently most common pilot mini-grids are solar and solar-wind hybrid based technologies, with diesel genset backup. Meanwhile, many of such rural communities produce agricultural residues and other biomass types that could be converted using biomass based power plants to meet their electricity demands.

This system of power generation, apart from providing the rural communities with self-sufficient energy, can also generate employment and other development opportunities for the rural inhabitants.

In most of the Senegal River Basin's rural communities, as in most sub-Saharan African countries, agricultural residue biomass is an abundant resource that can be supplied on a regular basis.

Biomass based electricity systems are expected to play a crucial role in the electrification of remote rural communities where agricultural residues are abundant (Sansaniwal et al., 2017). Already, biomass plays a very important role in global energy provision. In 2014, biomass

contributed 14% to global final energy consumption

Indeed it has been pointed out by Ekinci (Ekinci, 2011) and Rupf (Rupf et al., 2015) that for biomass systems to be economically viable, financial mechanisms must be put into effect, such as increasing market price of electricity produced from biomass plants to give an incentive to producers, and offering both long-term credits and tax breaks for investors. Rising fossil fuel prices and increasing concerns about climate change are creating a growing demand for new sources of raw material for sustainable electricity and heat production. Profitability may also be dependent on other factors such as the number of operating hours in the year, which directly affects the amount of electricity produced and fuel consumed, as well as investment expenditures. Previous studies on rural electrification have flagged the reduction of logistic problems and the convenient economics of considering distributed power generation facilities as close as possible to locations where biomass is abundant (Ekinci, 2011; Rupf et al., 2015) .

The overall objective of this analysis is to evaluate the availability of agricultural residues that could potentially converted into energy production to satisfy the energy demand. The concrete implementation of biomass reuse options is, in particular in rural areas is not included into this analysis. As for instance reviewed by Rupf (Rupf et al., 2015), this implementation rely, among other socio-economic factors, on institutional framework that will promote and support the implementation of such solutions in communities.

Main objectives of this analysis:

- Assess the potential of biomass at the community level for electricity generation: Estimation of how much waste is produced per unit or nuts, and then check whether there is sufficient production within a certain radius from a hypothetical plant;
- Estimate electricity demand at the community level;
- Analysis of difficulties to be taken into account: for example, in practice, the most difficult challenge is to collect the waste from many small and dispersed realities on the territory and transport it to the plants;
- Estimation of residues quantities requirement: based on minimum and optimal power of the plants, population needs, other energy sources;
- Analysis of the environmental impact of the introduction of these methods in reducing wood use and linkage with deforestation issues.

Methodological steps:

The following phases are involved:

evaluation of potential agricultural residues,

elaboration of scenarios and assessment to meet energy demands for given strategic goals

for soil conservation and organic nutrients preservation, at least 50% crop residues should be kept on the soil

Expected results / outcomes:

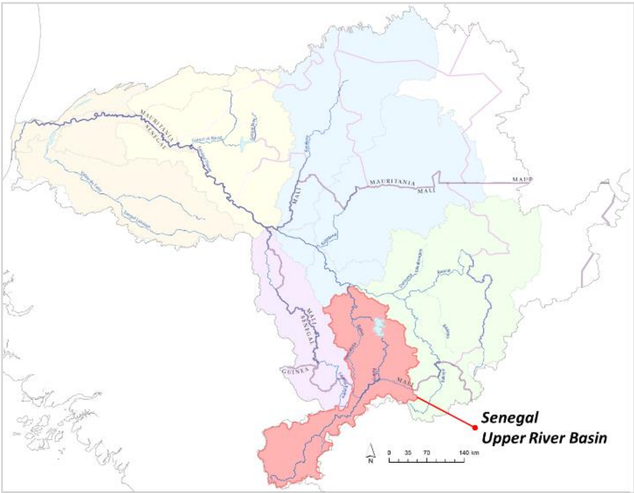
- Estimates of the energy potential of the residues in the Senegal River Basin by Administrative Units
- Analysis of deforestation occurring in the Senegal River Basin by Administrative Units
- calculate how much waste is produced per administrative unit, and then check whether there is sufficient production within a certain radius from a hypothetical plant.
- Optimization of cropland to reach required minimum production of residues to satisfy energy production
- Impact on deforestation reduction

3 Analysis of key indicators in the Senegal river basin

3.1 Forest Biomass loss

The analysis of forest loss indicator was focused on the Upper part of the Senegal river basin because this is the area where forests are present (as forest and mixed forest-shrubland-cropland- see also Figure 5).

Figure 5. Senegal river basin: the Upper river basin part.



The forest Biomass loss was assessed through these two indicators: the total tree cover loss and the Forest landcover:

3.1.1 Total tree cover loss

In order to have a rapid assessment of deforestation issue in the area of interest of the Senegal River Basin (mainly the Upper river basin in the Guinean region) the Hansen dataset with an adapted spatial resolution (30m) was selected (Hansen et al., 2013[2]).

This dataset allows indeed to estimate the tree cover loss between the period 2000- 2010 in the Senegal river basin.

Note that *"tree cover loss"* used in this report has not the same definition as for deforestation, as it includes also tree losses in natural forest, not necessarily due to human activity. Still, this is considered as a valid indicator/proxy to capture the risk and the magnitude of forest loss in a specific region.

Results: The Total tree cover loss for the year 2018 in the Upper basin has been estimated in about 40 kha of tree cover, equivalent to a 16% decrease since 2000. The analysis can be also specific for administrative units: here we propose an analysis just for the communes belonging to the Senegal River Basin and with important forest coverage. Very similar percentage loss was observed in the Mamou (lev. 2, Guinea; 57% tree cover) and Labe (lev2, Guinea) communes (respectively 17.1 and 16.1% loss), both considering all commune surface or only the surface physically within the river basin limit. In Faranah (level 2, Guinea; 68% tree cover) a lower loss was observed (about 8% in the period 2000-2018), while in Dabola (level 2; 30% tree cover) a loss of 13% was observed.

[2] The related Data is available on-line from:http://earthenginepartners.appspot.com/science-2013-global-forest. Accessed through Global Forest Watch on 26/03/2020. www.globalforestwatch.org).

3.1.2 Forest landcover

In the landcover classification, the class "forest" class is less restrictive if compared with tree cover class as defined in (Hansen et al.,2013) as defined by "all vegetation taller than 5 meters in height and it refers to all biophysical presence of trees and may take form of natural forest or plantations over a wide range of canopy densities".

Results: In Mamou (region, lev1, including Mamou, Dalaba and Pita communes at level 2) tree cover class is about 42% of its land area in 2010, while forest coverage (as resulting in ESA Climate change Initiative, Land Cover 2015) is about 71% of total land. In 2010, Faranah (region, lev1, including Mamou, Dalaba and Pita communes at level 2) had 1.34 Mha of tree cover, extending over 38% of its land area, while forest coverage from Landcover (2015) was about 79% (). In Kayes tree cover is mainly absent (<0.1% at lev1) and only present in Kéniéba (outside river basin), while forest land cover class is about 11%, while dominating classes are agriculture (45%, and about 50% if including also grassland) and shrubland 39%.

Figure 6. Global distribution of land cover in 2015 at 300m resolution for 3 regions in the river basin, ESA Climate Change Initiative,(ESA, 2017).

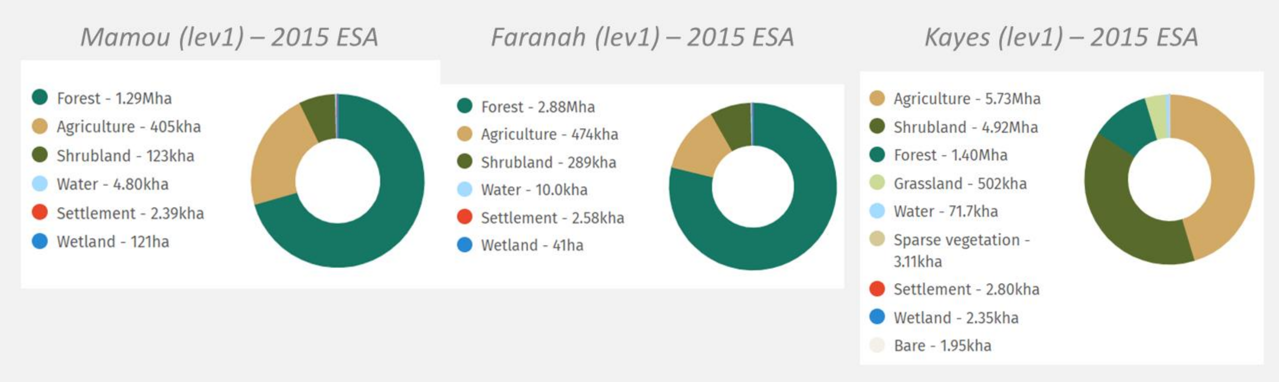
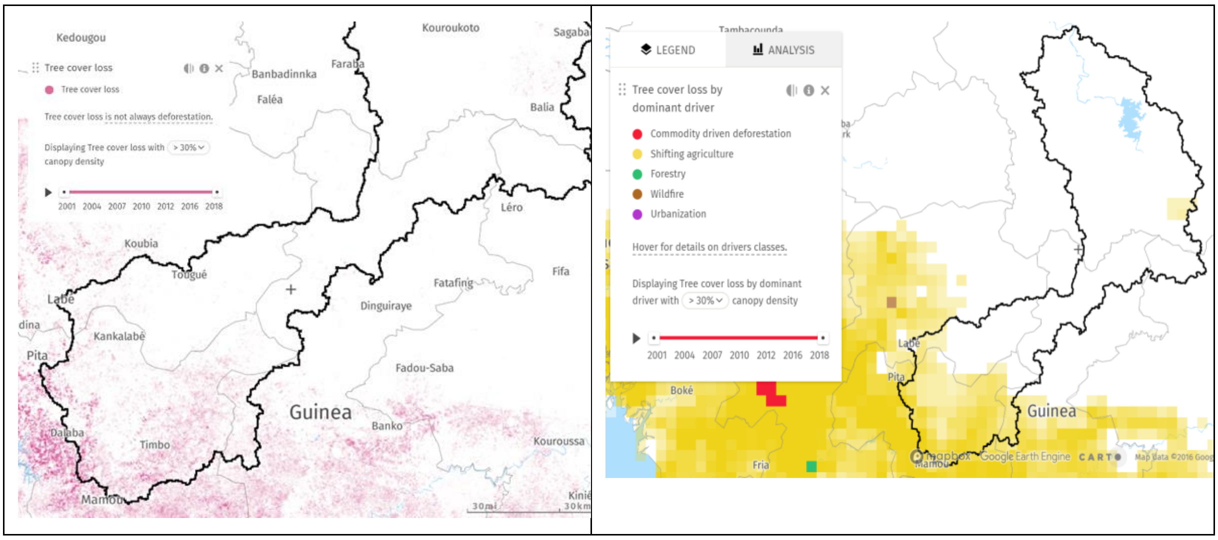
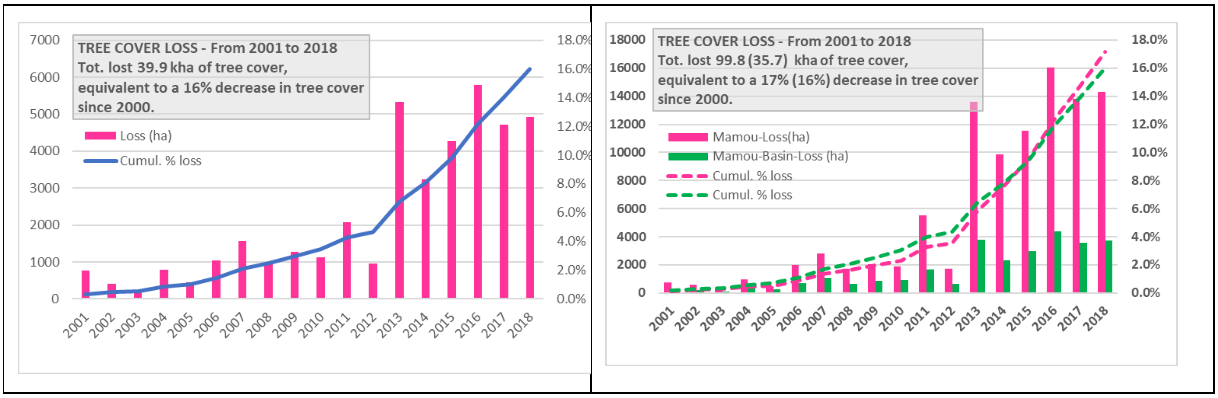


Figure 7. Tree cover loss in selected area of the Senegal river basin.





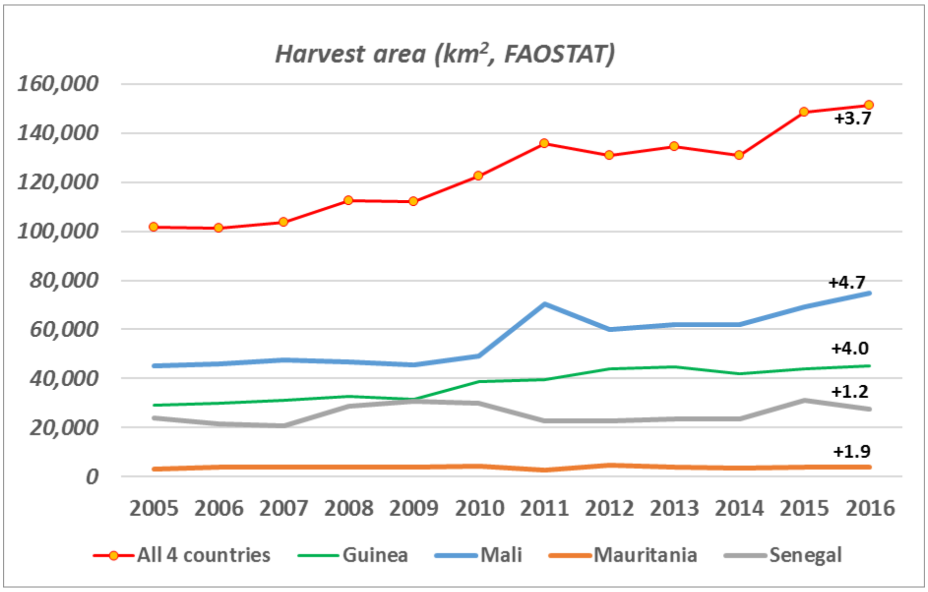
3.1.3 Crop distribution in the SRB

Agriculture is the key economic activity within the SRB as it accounts for 53 to 76% of employment resources (the highest share is in Mauritania). Its contribution to economy is important ranging from 15 to38% of the national GDP in 2017.. OMVS highlights the importance of agriculture as a main driver for economy, as it produces employment for the majority of the population and above all for its importance to reduce poverty and increase food security within the basin (OMVS, 2017). Agriculture accounts for 70 percent of total global freshwater withdrawals, making it the largest user of water. Water is used for agricultural production and along the entire agro-food supply chain, and it is used to produce, transport and use all forms of energy (FAO, 2011)

At the same time, the food production and supply chain consumes about 30 percent of total global energy. Energy is required to produce, transport and distribute food as well as to extract, pump, lift, collect, transport and treat water.

The total cropland accounted within the River basin delineation is about 14% of total harvested area in the four countries. It is interesting to note that the annual average increase is around 4% in the 4 countries for the period from 2005 (SPAM reference year) to 2016. These increases reported are higher for Mali and Guinea (4-6%) while less evident for Mauritania and Senegal (1-2%, see **Errore. L'origine riferimento non è stata trovata.**) (FAO, 2018).

Figure 8. Harvested area at National level for the period 2005-2016 (source: Faostat)



Cereals (like Sorghum, Fonio, Millet, and Maize) are the dominant crop types used across the SRB accounting for about 51% of the total harvested area. Maize is representing alone 8% of total area. Other important crops for surface occupancy are oil crops (16%), pulses (12%), Rice (7%) and Cotton (6%). Crops less diffused, but playing an important role in food items production, food security and household income, are vegetables (3%) and fruits (3%).

These statistics are derived considering all the SRB, but these figures are not changing much by disaggregating the statistics at country level (considering the portion of the SRB within each country):

- *Guinea (SRB harvest area: 132 000 ha):* Cereals are dominant crops (46%; Maize is at 13%) and Rice is very much diffused in the region accounting for about 21% of the total area; other important groups are Fruits, oils (8%) and vegetables and tubers (5-6%).
- *Mali (SRB harvest area: 224 000 ha):* Cereals are dominant crops (58%; Maize is at 10%) and oils crop group is also very much diffused in the region accounting for about 20% of the total area; other important crop is Cotton (13%)
- *Mauritania (SRB harvest area: 278 000 ha):* Cereals are dominant crops (53%; with 7% Maize) and pulses crop group is also very much diffused in the region accounting for about 34% of the total area; other important crop is Cotton (6%)
- *Senegal (SRB harvest area: 298 000 ha):* Cereals are diffused crops (35%; with 2% Maize) and oils and pulses crop groups are also very much diffused in the region accounting respectively for about 27% and 14%of the total area; other important crops are rice and vegetables (11% and 7%)

DOMINANT CROPS WITHIN THE

SENEGAL RIVER BASIN

Guinea: Cereals + Maize + Rice + Oils + Fruits // (Harvested area = 132 000 ha)

Mali: Cereals + Oils + Cotton // (Harvested area = 224 000 ha)

Mauritania: Cereals + Pulses + Rice// (Harvested area = 278 000 ha)

Senegal: Cereals + Oils +Pulses + Rice + Vegetables//(Harvested area = 298 000 ha)

Overall, the main agricultural crops, in terms of area cultivated and production capacity, are cereals like maize, sorghum, rice, oil crops and vegetables and tubers.

3.1.4 Crops residues and their energetic potential

Agricultural residues are obtained as products of agriculture biomass and by-products.. Agriculture is the mainstay of the Senegal river basin economy and this sector can potentially generate important volumes of useful residues to be converted to bioenergy source for domestic and commercial applications, mainly in rural areas where access to electricity is still limited or difficult.

Methodology to estimate crops residues availability and energetic potential

The annual quantity of agricultural residues generated has been estimated for 2016 in each administrative community in the Senegal River Basin together with their energy productivity. This is computedbased on reported cropped areas and reported crop yield under current management (WEFE-Senegal DATA set, OMVS. 2020). Residues produced from these crops and relevant to bioenergy are the *straw, stalk, husks, trunks* and sometimes their *peels* after harvesting and/or processing. The theoretical potential of crop residues was estimated using the output of crops (as dependentof annual yields productivity and surfaces used each year for a specific crop) multiplied by the residue to product ratio.

Following the example of previous studies (Kemausuor, 2014), a recoverability fraction was included to reduce the effective quantity of crop residues finally available for the energy production. This factor depends on the type of residues and in this case ranges 0.5 to 0.7 (meaning that 50% to 70% of the residues are finally available for energy process). This is also a way to take into account a minimum quantity of residues to be left on the soil to maintain soil fertility on the long therm.

Energy potential is dynamically estimated by the model based on the following equation:

$$EnPot = YLDc * AREAc * RPRc * RECFc * LHVc * EPE \quad \text{(eq. 1)}$$

Where

EnPot: Potential energy - MWh/yr

YLDc: annual productivity or specific dry yield (tons/ha) for crop c

AREAc: cropping surface (ha)

RPRc: crop specific residue to product ratio

LHVc: crop specific lower Heating value

RECFc: fraction of residues available for energy process

EPE: Electricity Power Plant efficiency Table 2 shows the potential amount of residues generated annually from selected crops (Residue to Product Ratio - *RPR*) and the corresponding energy that can be potentially produced from the given residues (Lower Heating Value - *LHV*).

Table 2. Summary of average residue production and energetic potential for several crops. RPR: Residue to Product Ratio, LHV: lower heating value as indicator of potential energy production. Sources: [1] ENDA 2010; [2] Ayamga et al. 2015; [3] Kemausuor et al. 2014; [4] Duku et al. 2011; [5] Arranz-Piera et al. 2017; [6] CIRAD 2017; [7] Phyllis2 (median values).

crop	residue	RPR min [1]	RPR max [1]	RPR [2]	RPR [3]	RPR [4]	LHV min [1]	LHV max [1]	LHV [4]	LHV [5]	LHV [6]	LHV [7]
		g/g	g/g	g/g	g/g	g/g	MJ/kg	MJ/kg	MJ/kg	MJ/kg	MJ/kg	MJ/kg
Maize	stalk	1	4.33	1.15	1.59	1.5	5.25	19.66	15.48	17.71		17.55
Maize	husks			0.23	0.2					17.22		
Maize	cobs	0.2	1.8	0.57	0.29		14.64	16.28		19.32		16.16
Rice	straw	0.42	3.96		1.66	1.5	10.9	16	15.56			17.19
Rice	husks	0.2	0.35		0.26		12.69	19.33		13.03	2.5	16.42
Millet	straw	1.1	2	5.53	1.83	3	12.39	12.39	15.51	17.76		16.77
Sorghum	straw	0.9	7.4	4.75	1.99	2.62	12.38	12.38	17	17		16.05

Cassava	stalk	0.16	1		0.06		17.5	17.5				
Cassava	peelings				0.25					13.38		
Groundnut	shell	0.48	1.2	0.35	0.37		15.66	15.66		17.43		17.61
Groundnut	straw	2.26	2.9	1.73	2.15		17.58	17.58				
Cowpea	shell				1.75							
Cocoa	pods	20	20		0.93	1	13.2	13.2	15.48	15.48		18.15
Yam	straw				0.5					10.6		
Sweet potato	straw				0.5							
Coconut	shell				0.25	0.6			10.61	18		19.43
Cotton	stalks				2.88							18.09
Cashew	shell	0.7	0.7								16.5	
Shea nut	shell	1.2	1.2								19.8	

Technical feasibility of the conversion of crops residues is not part of this assessment (see section objectives)since the technical option selected to produce energy depends on the type of residues and the technology adopted according to the energy use (among other for food systems; (Smith et al., 2015) for bioenergy, food and water or (Scarlat and Kougias, 2018), in addition to a wider conditions to ensure their sustainable use (Rupf et al., 2015).

As a consequence we just introduce through a concrete example some of the most common issues associated with this bioenergy source, and aspects to be taken into account for their implementation. The most difficult challenge is to collect the waste from many small and dispersed realities on the territory and transport it to the plants.

Example of implementation of a Combined Heat and Power (CHP) plant

- Plant specifications: The technology considered is a Combined Heat and Power (CHP) plant based on the Organic Rankine Cycle (ORC) with biomass boiler. This type of process is suitable for herbaceous biomass and straw. An electrical power of 600-2000 kW is suggested. A boiler efficiency of 85% and ORC cycle electric efficiency of 18.5% are assumed. This leads to an overall electrical efficiency of 15.72%. In order for the whole process to be economically viable, it is suggested that the plant must be in operation for a minimum of 7500 hours per year.
- Sufficient density of residues to set up a plant.

To do so, we evaluate how much crops residues are produced per land unit (or region - nuts), and then check whether there is sufficient production within a certain radius from a hypothetical plant. As an example, the minimum and optimal power of the plants, and therefore their requirements in terms of residues, are based on in Arranz-Piera (2017, 2018).

In the river basin of the Senegal, the sustainable functioning of a combined heat and power plant would require between 626 to 6737 ha of crops areas corresponding to a minimum of 125 harms of 5ha. These requirements can be recalculated and adjusted according to the crops mix of farms on a specific area. As a comparison, according to Arranz-Piera (2017, 2018) a minimum of 22 to 54 larger (10 ha) farms would need to be clustered to enable an economically viable biomass supply to a 1000 kWe plant. A 600 kWe plant would require 13 to 30 farms.

Table 3. Agricultural area and corresponding number of farms needed to operate the CHP plant, if all farms provide a combination of residues: 30% rice, 30% maize, 20% cassava and 20% millet residues.

Combined Heat and Power plant parameterization	
Area needed, max (ha)	6737.421
Area needed, min (ha)	626.527

Number of 5ha farms needed (max)	1347.484
Number of 5ha farms needed (min)	125.3054

Given these characteristics the minimum quantity of residues needed to operate a plant in an economically viable manner, and therefore the minimum amount of crop production and the area from which residues must be collected can be estimated (Table 3).

The requirements in terms of residues, crop production and area to feed a 600 kW CHP plant, based on information shown in Table 2 and the plant specifications reported above, knowing that a 600 kWe CHP plant operated for 7500 hours/year can potentially generate 4500 MWh/year of electricity.

To assess electricity production potential, a reference efficiency conversion factor of 18% was applied, using a downdraft fixed bed gasifier coupled to an Otto engine gas generator set

Table 4 Requirements of crop residues to operate a 600 kWe CHP plant for 7500 hours/year resulting in electricity generation of 4500 MWh/year.

		rice husk	rice straw	maize stalk	maize cobs	millet straw	sorghum straw	cassava stalk	groundnut shell	groundnut straw	yam straw	cocoa pods	cashew shell
Electricity to be produced	(MWh/yr)	4500	4500	4500	4500	4500	4500	4500	4500	4500	4500	4500	4500
Electrical efficiency of the plant		0.1572	0.1572	0.1572	0.1572	0.1572	0.1572	0.1572	0.1572	0.1572	0.1572	0.1572	0.1572
Lower Heating Value (LHV) of the residue (min)	(MWh/t)	3.5	3	1.5	4.1	3.4	3.4	3.7	4.4	4.9	2.9	3.7	4.6
Lower Heating Value (LHV) of the residue (max)	(MWh/t)	5.4	4.4	5.5	5.4	4.9	4.7	4.9	4.8	4.9	2.9	4.3	4.6
Residue-to-Product Ratio (RPR), min		0.2	0.42	1	0.2	1.1	0.9	0.16	0.48	2.26	0.5	20	0.7
Residue-to-Product Ratio (RPR), max		0.35	3.96	4.33	1.8	2	7.4	1	1.2	2.9	0.5	20	0.7
Crop productivity (min)	(t/ha/year)	2	2	3	3	1	1	2	1	1	5	0.4	0.5
Crop productivity (max)	(t/ha/year)	2	2	3	3	1	2	2	1	1	5	0.4	0.5
Potential energy of residues per unit surface (min)	(MWh/ha/year)	1.40	2.52	4.50	2.46	3.74	3.06	1.18	2.11	11.07	7.25	29.60	1.61
Potential energy of residues per unit surface (max)	(MWh/ha/year)	3.78	34.85	71.45	29.16	9.80	69.56	9.80	5.76	14.21	7.25	34.40	1.61
Residue required (max)	(t/year)	8179	9542	19084	6982	8419	8419	7737	6506	5842	9871	7737	6223
Residue required (min)	(t/year)	5301	6506	5205	5301	5842	6091	5842	5964	5842	9871	6657	6223
Crop production needed (max)	(t/year)	40894	22719	19084	34910	7654	9355	48355	13554	2585	19742	387	8890
Crop production needed (min)	(t/year)	15146	1643	1202	2945	2921	823	5842	4970	2014	19742	333	8890
Area needed (max)	**(ha)**	**20447**	**11360**	**6361**	**11637**	**7654**	**9355**	**24177**	**13554**	**2585**	**3948**	**967**	**17780**

Area needed (min)	**(ha)**	**7573**	**821**	**401**	**982**	**2921**	**412**	**2921**	**4970**	**2014**	**3948**	**832**	**17780**
Number of 5ha farms needed (max)		4089	2272	1272	2327	1531	1871	4835	2711	517	790	193	3556
Number of 5ha farms needed (min)		1515	164	80	196	584	82	584	994	403	790	166	3556

Table 4. shows individual requirements for each type of residue. In reality, a household small farming as well as a smaller consortium of small farmers, would typically produce more than one type of residue. As an example, Table 3 shows the requirements assuming that all household small farms have a combination of crops, normally produced to satisfy both food demand and market selling: 30% rice, 30% maize, 20% cassava and 20% millet.

Financial Feasibility: Financial feasibility is finally a key element that is even more complex and should be assessed at local scale depending on national economic and incentive frameworks of each of the 4 countries. As an example, (Arranz-Piera,2018) 'analysis for a 1000 kWe CHP plant case indicated that such investment would not be viable under the current renewable feed-in-tariff rates in Ghana; increased tariff by 25% or subsidies from a minimum 30% of investment cost would be needed to ensure viability using internal rate of return as an indicator.

3.1.5 Energy Demands

In order to estimate the potential impact of such new energy availability on several demands, at this stage two important potential demands have been considered and estimated:

- Population energy demand (specifically for household demands) and
- Irrigation energy demand

Population demand

Population energy demand has been estimated for the baseline year (2016) and it is based on current population distribution across the river basin and population estimation for 2025 as defined in the SDAGE (defined as annual population trend rates). The energetic demand is than based on household energy demand per capita estimated at national level for the two reference years (see Table 5 for details).

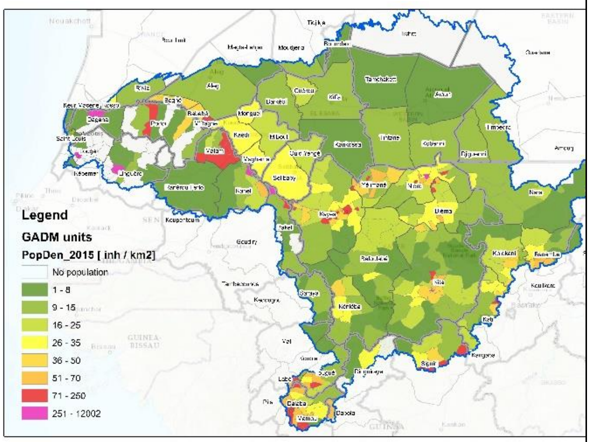
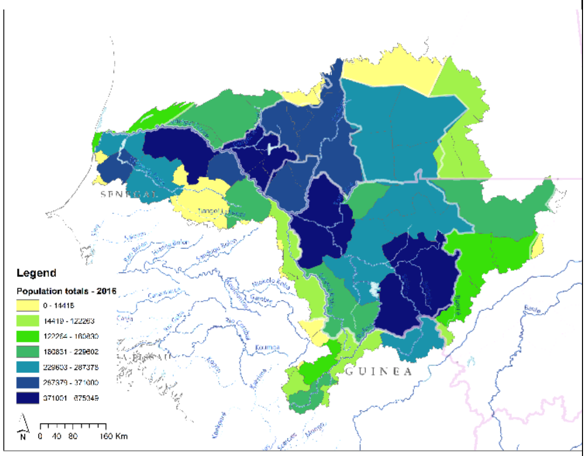
Table 5. Energetic demand by households as kwh per capita.

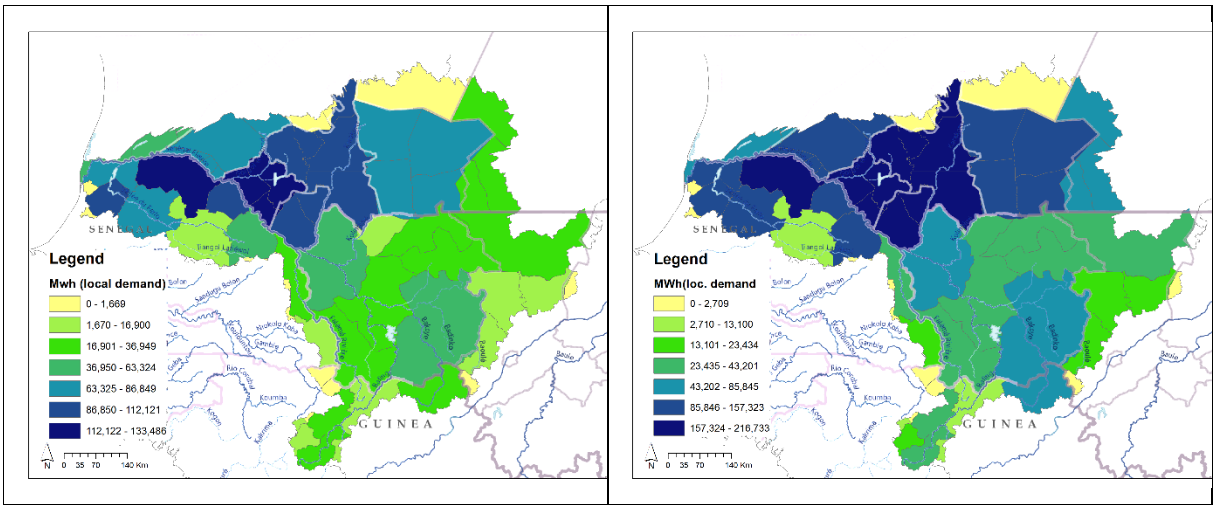
	Energetic demand by households as kwh_capita	
	2016	**2025**
Guinea	140	182
Mali	78	102
Mauritania	302	393
Senegal	298	387

Source: https://unstats.un.org/unsd/energystats/dataPortal/

In this table a reference energy demand per household is provided based on literature (Source: https://unstats.un.org/unsd/energystats/dataPortal/). These values are available at country level and even if they can be variable at regional level, this is an average level that would be useful to define a consumption indicator. It would be also possible to easily modify and disaggregate this values if more detailed data would be provided.

Figure 9. Spatial distribution at administrative level 2 (GADM) of population used for Energy demand estimation and household energy demands distribution for two different reference years.

Population density (inh/km^2) - 2015	Population totals (at Admin level2 for Guinea, Mali and Senegal, Admin. Level1 for Mauritania) - 2016
	
HH energy demand (Mwh) - 2016	HH energy demand (Mwh) - 2025



Irrigation demand

Operation of irrigation requires lifting and moving water around the farms, usually by using pumping systems that consume an important amount of energy as water is a heavy liquid. Pumping costs are indeed a major component of irrigation costs and their energy requirements need to be taken into account. To estimate this energy demand, the following assumption were made:

- As energetic demand is highly dependent on the total dynamic head (or quote), a model parameter to represent the depth of lifting has been introduced; thus end-users can easily change this value and assess the new energetic costs. For the baseline scenario, a value of 15m is used (this is positive, even if it corresponds to the soil depth, or total dept to be considered to lift and move water).

Pump efficiency, that is generally higher for electric pumps if compared with diesel pump, is expressed in this model has the energy required to lift 1 ML (mega litre) of water for 1 m of head; for the baseline scenario, the standard value of 5.9 kwh/ML/m head is used (Department of Industry and Science Australian Gov., 2020)Energy demand for irrigation is then estimated by our model based on the following equation:

$$EnD_{Irr} = PumpEff * THead * \mathrm{IRRfrac} * \mathrm{WatReq} * 10^6 \qquad \text{eq. 2}$$

Where:

EnDIrr: Total irrigation water demand as Mwh;

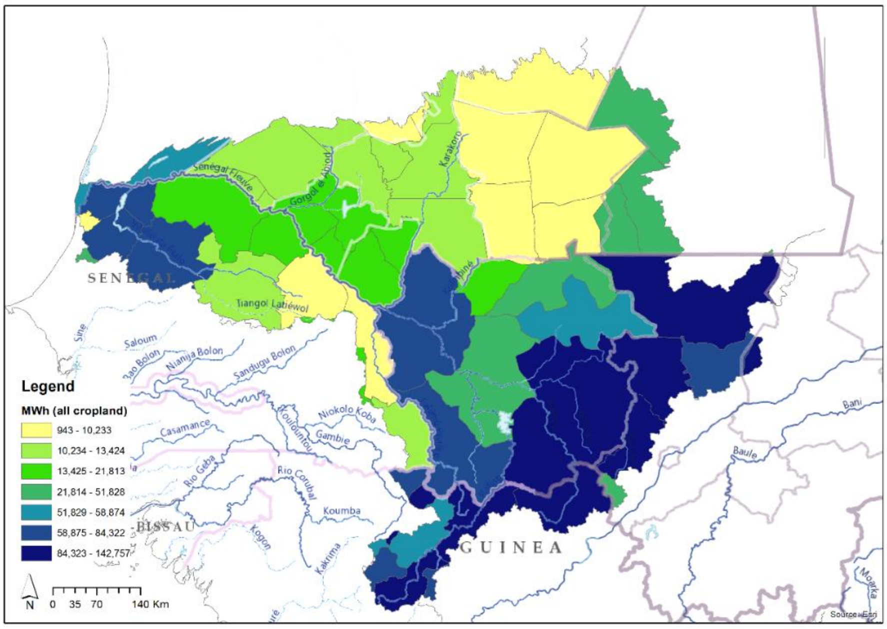
PumpEff: specific pump efficiency expressed as the energy required to lift 1 ML (mega litre) of water for 1 m of head;

THead: Total dynamic head in m

IRRfract: Surface of crop area to be potentially irrigated (%)

WatReq: Average water requirement specific for each crop and region (m3/cropping season/ha)

Figure 10. Energy demand required to potentially irrigate current cropland to 100% requirement.



Food demand

Food demand was calculated by combining diet habits of local population with the average dietary energy requirement as defined by FAO (FAO et al., 2014; FAO, 2018a). The latter was estimated

At country specific values as estimated by FAO national statistics (see Table 6). Diet habits were based on the annual per capita quantity of each food crop consumed.

Table 6. Current Average dietary requirements of the country

Pays	ADER – ref. 2015-2018	Avg Food supply 2015-2017	Scenario: Avg Food supply 2025
Guinea	2350	2806	3000
Mali	2000	2881	3000
Mauritania	2250	2808	3000
Senegal	2280	2564	3000

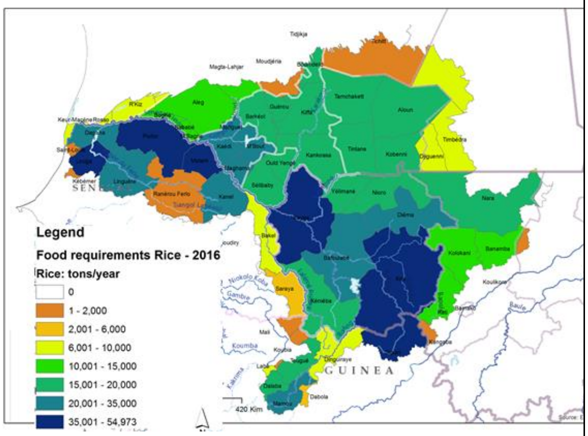
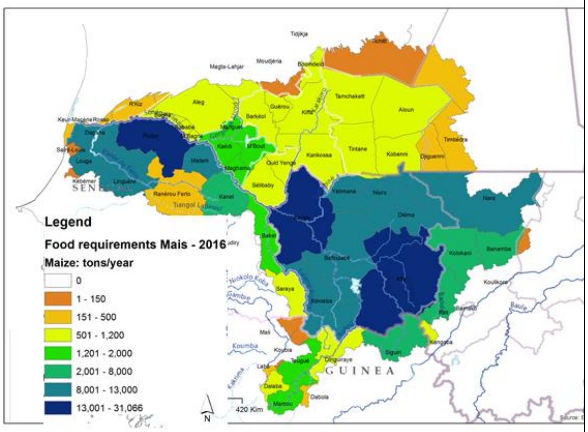
These are national level, including an average between urban and rural areas. Anyway, we can consider this value as a target to optimize food self-sufficiency capacity in the Senegal River basin. According to FAO Food security Indicators each country has a specific minimum and average dietary energy requirement set up and updated annually based on specific statistics for food consumption for different population types.

Currently, the linkage between food security and agriculture is particularly strong in SRB countries as population diet is very much dependent on agricultural food commodities such as cereals, roots and tubers: indeed, share of Dietary Energy Supply derived from cereals, roots and tubers is 52% for Mauritania, about 60% for Guinea and Senegal and 67% for Mali.

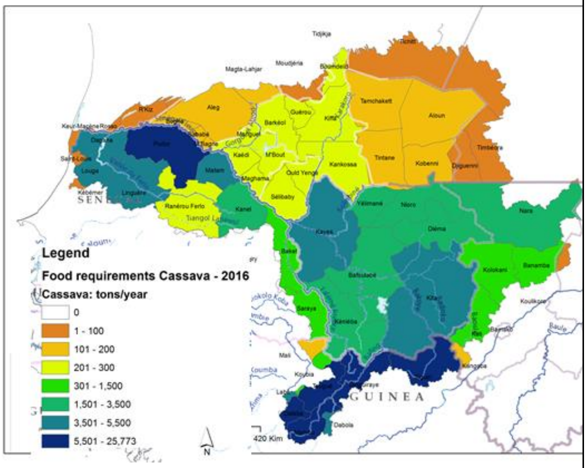
Table 7. Food supply quantities for main food groups at National level as estimated by FAOSTAT in 2017 and an example of projection to 2025, considering an average requirement of 3000 Kcal/cap/day /now is about 2600-2800)

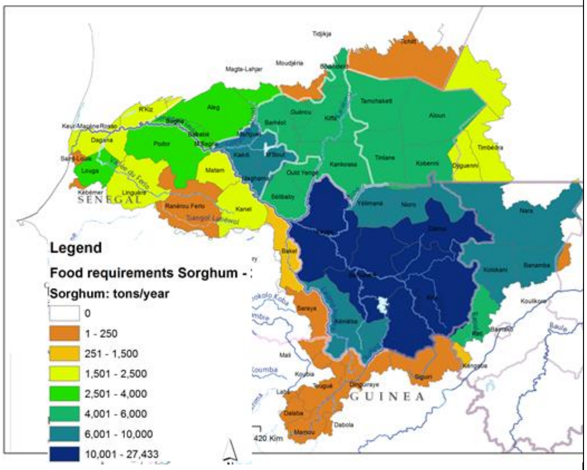
	Food supply quantity (kg/capita/yr) - 2017				Food supply quantity (kg/capita/yr) - 2017			
	Guinea	Mali	Mauritania	Senegal	Guinea	Mali	Mauritania	Senegal
Group_name								
Alcoholic Beverages	3.5	35.8	0.1	2.8	3.6	36.7	0	3.2
Animal fats	0.2	0.6	1	0.3	0.3	0.6	1.1	0.3
Aquatic Products, Other	0	0	0	0	0	0	0	0
Cereals - Excluding Beer	195.3	245.9	187.2	227.7	209.7	252.3	197.6	261.7
Eggs	1.9	0.7	2.3	1.7	2	0.7	2.4	1.9
Fish, Seafood	10.1	9.3	9.2	18.1	10.6	9.5	8.1	19.8
Fruits - Excluding Wine	89.6	48.3	11.9	20.6	96	49.1	12.4	23.5
Meat	13.1	23.7	31.1	14.1	14	24.3	32.8	16.2
Milk - Excluding Butter	16.6	88.2	89.8	11	17.9	90.5	94.8	12.6
Miscellaneous	2.6	2.3	6.9	0.1	2.8	2.3	7.2	0.1
Offals	1.9	3.4	3.9	1.8	2.1	3.5	4.1	2.1
Oilcrops	10.8	6	0.7	6.6	11.5	6.1	0.7	7.5
Pulses	4.4	9.9	10.1	4.1	4.8	10.1	10.6	4.7
Spices	0	0.8	0.1	0.6	0	0.8	0	0.7
Starchy Roots	133.2	33.2	9.3	23	143	34	9.8	26.4
Stimulants	1.4	0.8	3.4	1.1	1.1	0.7	3.5	0.8
Sugar & Sweeteners	15.1	10.9	39.4	18.4	16.2	11.2	41.6	21.1
Sugar Crops	0			0	0			0
Treenuts	0	2.9	0	0.9	0	3	0	1.1
Vegetable Oils	15.1	6.4	14.4	17	16.2	6.5	15.1	19.5
Vegetables	50	90.3	36.4	69.4	53.7	92.7	38.4	79.7

Figure 11. Extrapolation of food demands/requirements at sub regional level, based on food requirements per capita and population distribution at sub regional level current and future.

RICE	MAIZE
	

CASSAVA	SORGUM





Nevertheless, there are other aspects that could potentially affect food crop insecurity, such as post-harvest losses, limited accessibility to market, lack of infrastructure for food transport and storage, and a cropping system highly sensitive to local and seasonal conditions. In order to incorporate all these issues into the analysis of food production, we used a food security factor, measuring the effective quantity of food available for consumption, ranging from 20% for most crops to 50% for rice and oil crops.

3.1.6 Livestock distribution and forage demand

Livestock breeding is a key activity in the SRB both for its economic and social importance. The practice of breeding is essentially extensive and the majority of livestock animals are small ruminants (sheep and goats) and cattle. Transhumance is also widely practiced on the whole river basin. In terms of quantities, as better evident by following section, the number of animals is not currently so high by impacting much water resources (if compared with irrigation cropping system and AEP demands). Indeed livestock density ranges from a minimum of 1.7 heads/km^2 in Tagant area (Mauritania) to a maximum of 460 heads/km^2 in Louga region (Senegal). The issue is more with the management of water and forage input for animals as livestock requires a constant supply throughout the whole year of both water and feed. Indeed for water supply livestock farming requires constant maintenance of small floods, micro reservoirs systems and groundwater points for the inundation of pastural areas and for animal beverage. Also feeding is a key issue because of the competition of land with other agricultural activities and because of the potential conflict between cropping and animal free breeding in the fields.

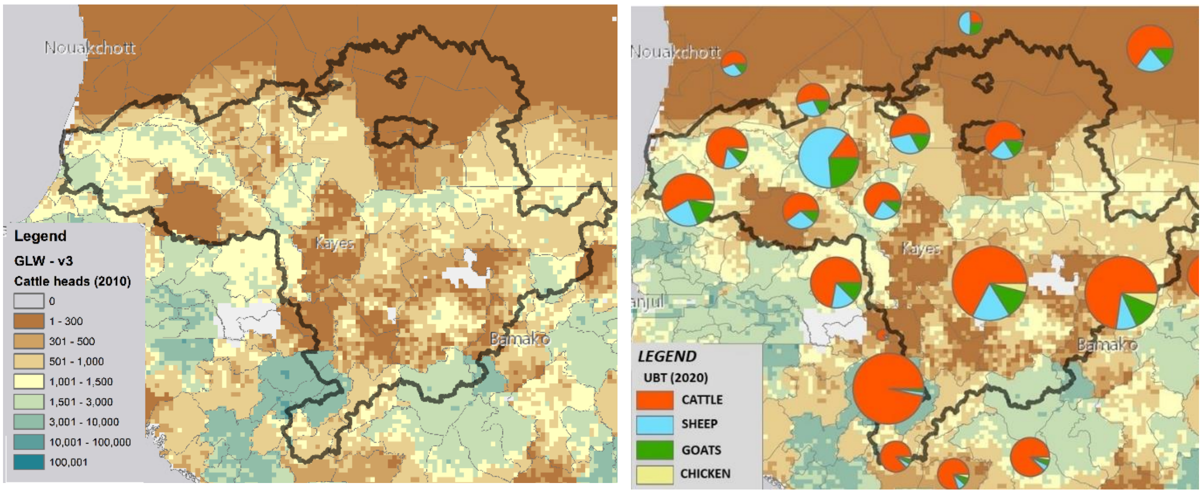
Table 8. Livestock animal heads in the SRB by Subregional Level1 (GADM) as estimated for year 2020. Original data derived by (Gilbert et al., 2018a) and projected by assuming annual growth rate of 5% for Cattle and 6% for other animals.

GAD_NAME0	GAD_NAME1	N_CATTLE	N_GOAT	N_SHEEP	N_CHICK	UBT_TOT
Guinea	Faranah	326,195	240,740	201,262	1,875,264	327,870
	Kankan	548,928	232,030	194,688	1,821,846	503,778
	Labé	1,981,749	260,973	218,394	2,049,284	1,658,039
	Mamou	342,524	154,414	129,047	1,213,103	316,996
Sub Total		3,199,396	888,157	743,390	6,959,498	2,806,683
Mali	Kayes	1,535,077	2,197,364	2,323,082	10,462,353	1,830,311
	Koulikoro	1,571,218	2,071,617	1,238,248	14,768,936	1,734,024
	Ségou	658,368	1,029,951	469,840	3,104,315	716,638
Sub Total		3,764,663	5,298,932	4,031,170	28,335,604	4,280,973
Mauritania	Assaba	346,875	799,736	1,183,468	1,084,224	519,583
	Brakna	239,787	577,777	775,632	654,329	355,902
	Gorgol	217,137	2,799,255	5,596,003	821,869	1,187,554
	Guidimaka	370,383	435,553	778,088	847,374	447,185
	Hodh ech Chargui	570,496	970,767	1,153,360	922,213	711,867
	Hodh el Gharbi	378,965	701,860	806,008	1,086,413	486,556
	Tagant	59,509	473,277	675,041	170,276	185,055
	Trarza	150,287	257,042	492,174	620,922	215,316
Sub Total		2,333,438	7,015,267	11,459,775	6,207,621	4,109,019
Senegal	Kédougou	48,134	16,121	28,098	79,341	44,600
	Louga	651,182	1,448,597	1,589,916	3,498,550	910,016
	Matam	317,019	477,225	919,705	271,041	431,745
	Saint-Louis	505,398	560,657	625,546	2,830,339	570,300
	Tambacounda	758,649	1,047,070	994,776	1,047,498	849,240
Sub Total		2,280,381	3,549,670	4,158,040	7,726,770	2,805,901
Total		11,577,879	16,752,026	20,392,375	49,229,493	14,002,576

More specifically different livestock farming systems can be identified in the SRB. In Guinea, the livestock is essentially sedentary. This is because of the abundance of pastural areas and also because this is the more humid part of the river basin, where animals can quite easily find water for beverage during all the year. Indeed livestock farming is very important and occupies about 7% of the population (OMVS, 2018).

Catlle is dominant if considered as UBT (Unite de Betail Topical; where 1 UBT = 250 kg and 1 cattle = 0.8 UBT, Goat and sheep = 0.1-0.13 UBT and Chickens = 0.007 UBT), indeed it is about 90% in Guinea region and the dominant subregion is Labe. Animal beverage is based both on water points (for superficial groundwater or fractured systems) and also on the main rivers such as the Bafing, the Faleme and the Bakoye.

Figure 12. Livestock cattle heads number for year 2010 as derived by (Gilbert et al., 2018b) (left); Share of importance of different livestock category reported as UBT (Unite Betail Tropical) and summarized at sub regional level (GADM level 1).



In Mali the livestock is essentially extensive and it is the second source of income for rural system. In Kayes and Koulikoro the total number of Cattle (estimation for 2020) is about 3.1 M heads accounting for about 80% of total cattle in the Mali region (27% of the whole SRB).

In Mauritania the livestock is generally semi sedentary or based on seasonal transhumance. Indeed if compared with the area in Guinea, here, especially during dry season, animals are obliged to move looking for pasture and water for beverage. Indeed the figures are also important for this country as for example total cattle is about 20% of the total SRB basin (about 2.35 M of heads for 2020).

In Senegal most of the catlle is located in Goudiry, Podor and Linguere, and this accounts for about 10% of total cattle living in the SRB. Apart from these native animals, it is important to remember that livestock from other regions transhumance towards the Senegal river, due to the very acute water problem faced by the herds during the 8 to 9 months of the dry season. Anyway the number and size of these herds are difficult to quantify because there are no reliable statistics on transhumance to the river from the hinterland.

In general Livestock density in the SRB is not very high across different areas and countries. If we consider maximum cattle density it ranges from a minimum of 1.7 heads/km^2 in Mauritania (Tagant) region to a maximum of 463 heads/km^2 in Senegal (Louga) region. The average cattle density in the SRB is about 14 with a minimum in Mauritania (7.6 animals/km^2) and a maximum of 24.2 in Guinea.

Forage and water demands indicators

In order to take into account of livestock component in the WEFE Nexus assessment and optimization analysis, as presented in the following sections, two indicators were estimated at subregional level (Level 2 of GADM classification) for forage average annual demand and water requirements. For this analysis we estimated a total amount of forage requirement, without differentiating across the type or source of this input: indeed the objective is to have a constraint or optimization objective to be used for the analysis. The forage used to feed the animals would also depend on the type of breeding system, if sedentary or based on seasonal transhumance: to take into account this aspect not all forage demand is considered as dependent on the crop residues. To this scope a correction factor is introduced in the model and this is adaptable according to specificity of the area or the regions. In this preliminary analysis a factor of 50% is used: this implies that animals would derive their feeding requirement for an half by crop residues and for the remaining quote from pastural areas. The average forage quantity as defined in literature for UBT in the Sahel region was set at 5 kg of dry weight per UBT per day (Ickowicz and Mbaye, 2001; JGRC, 2001; Rhissa, 2010). The water requirement was set to an average of 22 l/UBT/day. In the case of forage demand it is also important to consider the period in which the feed is needed: to this scope the number of days required can be also changed depending of the habits, uses and regions. For this analysis the length is fixed to 212 days, corresponding to the dry period.

Under these assumption the following indicators were estimated at subnation level (regional level 2 of GADM classification, (FAO, 2015):

- ForageDemDryP: forage annual demand (for the dry period of 212 days) defined as:

$$ForDemDry_i = TotNUBT_i * Daysdry * DailyFor \quad \text{eq. 3}$$

Where i is for the administrative region

- ForageDemHumP: forage annual demand (for the humid period of 153 days) defined as:

$$ForDemHum_i = TotNUBT_i * (365 - Daysdry) * DailyFor \quad \text{eq. 4}$$

- WaterDemand: annual water demand (tot m3)

$$WatLivDem_i = DailyDem_i * TotNUBT_i * 365 * 10^{-3} \quad \text{eq. 5}$$

Table 9. Estimated indicators accounting for: Forage livestock demand at regional level for dry period and humid period and total water demand at annual scale.

GAD_NAME0	GAD_NAME1	Forage_d1_tonsyr	Forage_d2_tonsyr	Forage_tot_tonsyr	water_demand_tot_m3
Guinea	Faranah	347,543	250,821	598,363	2,632,799
	Kankan	534,005	385,390	919,395	4,045,339
	Labé	1,757,521	1,268,400	3,025,921	13,314,052
	Mamou	336,015	242,502	578,517	2,545,475
Sub Total		2,975,084	2,147,112	5,122,196	22,537,665
Mali	Kayes	1,940,129	1,400,188	3,340,317	14,697,395
	Koulikoro	1,838,065	1,326,528	3,164,594	13,924,212
	Ségou	759,636	548,228	1,307,864	5,754,603
Sub Total		4,537,831	3,274,944	7,812,775	34,376,210
Mauritania	Assaba	550,758	397,481	948,238	4,172,249
	Brakna	377,256	272,265	649,521	2,857,894
	Gorgol	1,258,807	908,479	2,167,286	9,536,060
	Guidimaka	474,016	342,097	816,113	3,590,896
	Hodh ech Chargui	754,579	544,578	1,299,158	5,716,294
	Hodh el Gharbi	515,750	372,216	887,965	3,907,047
	Tagant	196,159	141,567	337,726	1,485,994
	Trarza	228,235	164,717	392,952	1,728,990
Sub Total		4,355,560	3,143,400	7,498,960	32,995,424
Senegal	Kédougou	47,276	34,119	81,395	358,137
	Louga	964,617	696,162	1,660,779	7,307,428

GAD_NAME0	GAD_NAME1	Forage_d1_tonsyr	Forage_d2_tonsyr	Forage_tot_tonsyr	water_demand_tot_m3
	Matam	457,650	330,285	787,935	3,466,913
	Saint-Louis	604,518	436,280	1,040,798	4,579,511
	Tambacounda	900,194	649,669	1,549,863	6,819,397
Sub Total		2,974,255	2,146,514	5,120,770	22,531,386
Total		14,842,730	10,711,971	25,554,701	112,440,685

3.1.7 Reference SCENARIOs

Different assumptions can be introduced to estimate the potential energy available based on different scenarios. To this scope a Baseline scenario was derived by considering current crop agricultural practices at river basin level as a reference. In this study the scenarios proposed are just example: a scenario in this case should be considered as a set of modified strategies affecting the capability to produce crop residues and to produce more or less bioenergy: as an example a scenario is a measure or strategy that influence cropland allocation, crop productivity as based on new practices (for example by using more fertilization or more irrigation), cropland expansion, agriculture intensity (defined as the effective use of cropland), etc. These scenarios can be changed dynamically based on new data and new assumptions. For this example, analysis, the following scenarios have been considered to estimate different amounts of crops residues and their energetic potential.

A. **BASELINE :** The reference year to setup this scenario is 2016. Indeed for this year, data for crop production and productivity are available from a local OMVS data collection, performed at subnational level in the framework of the WEFE Senegal project. Average values for parametrization of LHV and RPR for all the crops are considered. RECF fractions 0.5 for straw residue types and 0.7 for husks. EPE is equal to 0.1572 (as for all the scenarios). See eq.1 for more details about the prameters.

The different scenarios selected for this analysis excluded the hypothesis of extending the crop area, that would represent an important change. Indeed the interest of all these scenarios is to estimate the energetic potential based on the current available cropland and considering a their better exploitation , without necessarily requiring a more intensive use of land. To this scope, after the analysis of current and modified conditions an optimisation tool is used to assess the optimal crop distribution.

B. **Scenarios with changes of "CROPS AREA DISTRIBUTION"** (Names: Area.1, Area.2 and Area.3).

The energetic potential with a different mix of crops is assessed considering all baseline parameters, while changing the amount of cropping areas for some specific crops.

SCENARIO	DESCRIPTION	FOCUS
AREA 1	Increase of peanuts surface of 20%, by reducing proportionally other crops, thus without any impact on the total cropland.	+ Peanuts
AREA 2	Increase of rice surface of 20%, by reducing proportionally other crops, thus without any impact on the total cropland	+ Rice
AREA 3	Increase of maize surface of 20%, by reducing proportionally other crops, thus without any impact on the total cropland	+ Maize

C. **Scenario with changes of CROPS AREA DISTRIBUTION and YIELDS (AreaYield.1).**

The energetic potential is assessed considering all parameters as for the BASELINE while changing the amount of cropping area and yield productivity for some specific crops:

1. Increase of maize surface of 20%, by reducing proportionally other crops, thus without any impact on total cropland
2. Increase of maize yields of 20%

SCENARIO	DESCRIPTION	FOCUS
AREA-YIELD 1	Increase of maize surface of 20%, by reducing proportionally other crops, thus without any impact on total cropland + Increase of maize yields of 20%	+ Maize + Better agricultural practices

Scenario with changes of YIELD (Yield.1)

The energetic potential is assessed considering all parameters as for the BASELINE,while changing yield productivity for all crops:

SCENARIO	DESCRIPTION	FOCUS
YIELD 1	Increase of crops yield productivity by +20% annually, without any changes of the crops distribution and area	+ Better agricultural practices

4 Results and discussion

4.1 Energetic potential at regional level for the Baseline scenario

The potential energy from the residues for several dominant crops in Senegal river for the year 2016 are reported in **Errore. L'origine riferimento non è stata trovata.** at administrative level 2 (communes) and, in **Errore. L'origine riferimento non è stata trovata.**, at administrative level 1 (department or regions) and at country level (area within the River Basin). By considering total values, the crops dominating the energy production potential are rice, followed by peanuts and maize with respectively 27, 24 and 21 % of the total energy production potential (Figure 15). At country level rice is dominant for Mauritania (76%) and Senegal (44%), while for Guinea maize is potentially the most productive for energy from residues and for Mali the dominant crops are sorghum and maize with respectively 27 and 24%. For all crops, it is estimated that between 50 and 70% of field based residues could be available for collection, depending on the crop and on the residue type.

Total crops residues generated in 2016

7 Mt in the Senegal River Basin

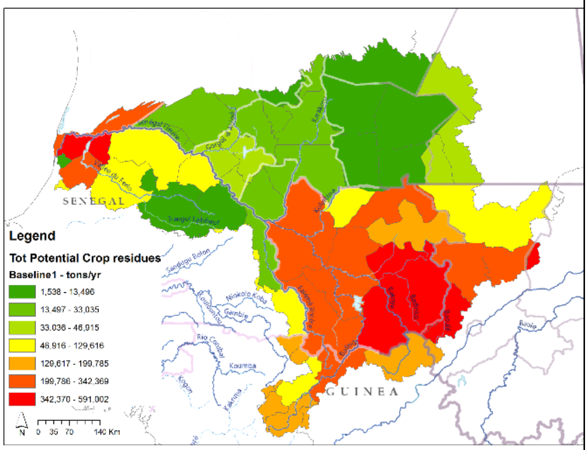
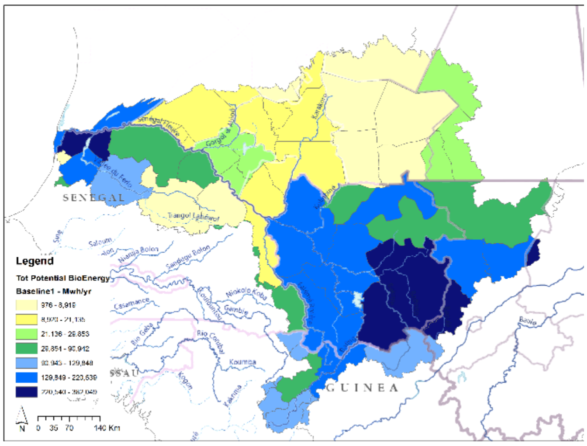
TOTAL ENERGETIC POTENTIAL derived from crops residues

Senegal River Basin = 4.4 Million of MWh yearly distributed per country, assuming all residues processed

Guinea	Mali	Mauritania	Senegal
24%	50%	7%	19%

For Senegal and Mauritania, the dominating crop to be considered as reference for current collection of residues is rice (Figure 14). This is the first crop cultivated in the valley area for residues production, specifically in the region of Dagana for Senegal and in the area of Keur-Macene Rosso and R'Kiz for Mauritania (Figure 14, b). In addition, rice is also relatively important in Guinea in the region of Dinguiraye. In Guinea, the dominant crop for residues production is maize, above all in Labe and Dinguiraye regions. In Mali, the picture is much more diversified, with an additional important contribution of other cereals, such as sorghum and millet, being much more spread in the rural and dry areas: the most productive potential area in Mali is Kayes, as this is the region where agricultural is more diffused within the Senegal river basin.

Figure 13. Total crop residues generated and potential energy from dominant crops in Senegal river for the year 2016.

Total residues – tons/yr	Bioenergy potential – Mwh/yr
	

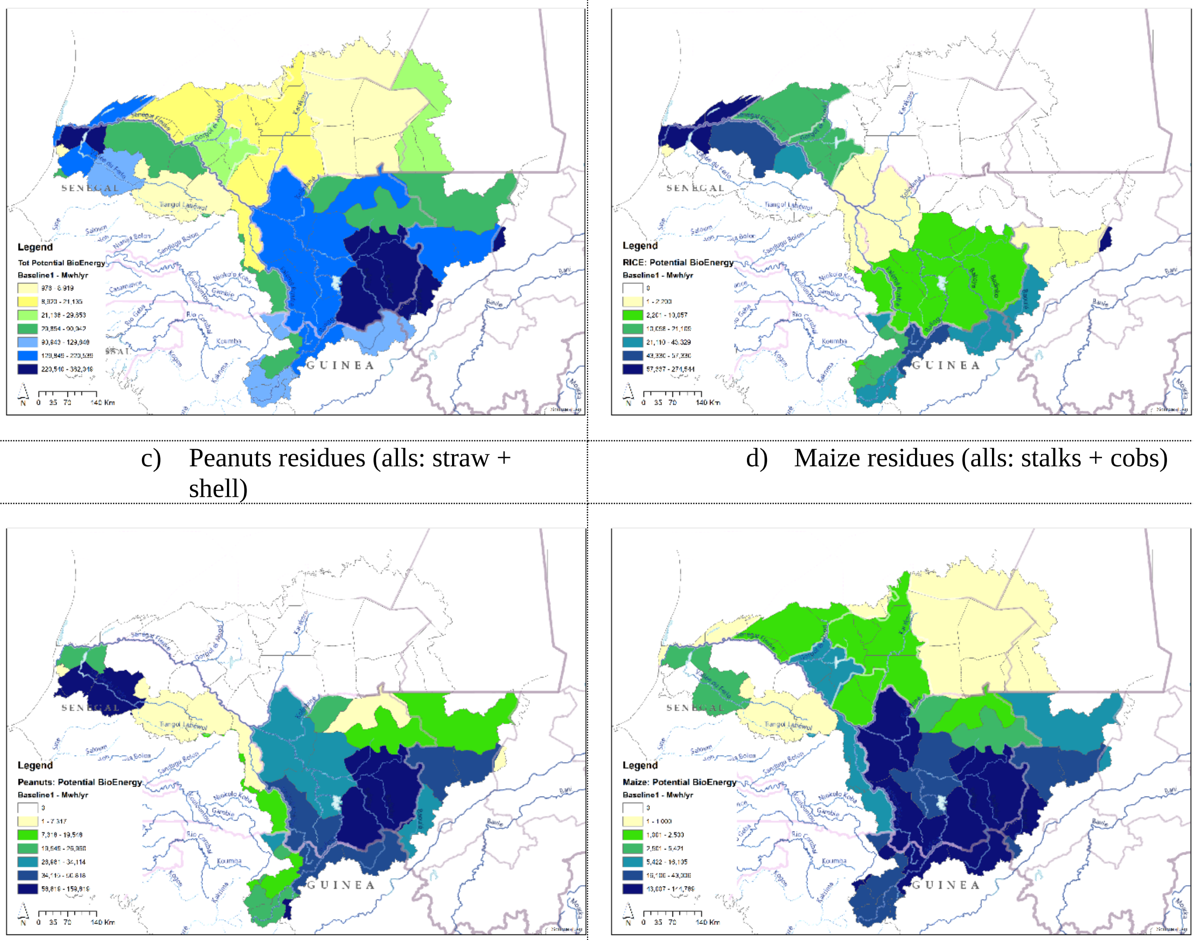
In 2016, the total crop residue generated was approximately 7 Mt in the Senegal River Basin. **Therefore, the resulting total energy potential for the Senegal river Basin is about 4.4 Million of MWh yearly, of which 50% from Mali, 24% from Guinea, 19% from Senegal and 7% from Mauritania** (Figure 13). This estimation considers crops production in 2016 and the conversion into energy (as detailed in the methodological section) by assuming the capability of 600 kW CHP plants as a reference for energy conversion estimation.

4.1.1 Baseline: The spatial distribution of crop residues

This availability is regionally more concentrated in the area of Kayes in Mali, in Guinea and for Senegal and Mauritania is mainly concentrated in the lower valley, where most of agricultural activities are aggregated (Figure 14). The regional distribution is an important aspect to be considered when the objective is to satisfy different energetic demands that can have a different spatial distribution, thus limiting the capability of use such bioenergy resource. For this reason it is also important to perform the assessment at a reasonable spatial scale, without requiring any transport of the energy. Indeed it should also be considered that such bioenergy strategy is mainly aimed to satisfy the need of rural household, that would live in rural areas where also agricultural crops are available (maybe just some specific crops and not the more energetic efficient ones). We can assume that bioenergy produced is used locally both to satisfy energetic demand for habitants and eventually for irrigation. It's for this reason that the strategy of exploit crop residues for energy is considered generally effective and realistic if applied in rural areas, where residue can be easily collected and transformed locally in small plants.

Figure 14. The potential energy from the residues for several dominant crops in Senegal river for the year 2016.

a) Total bioenergy | b) Rice residues (alls: husk + straw)



c) Peanuts residues (alls: straw + shell) | d) Maize residues (alls: stalks + cobs)

e) Sorghum residues | f) Tubers residues

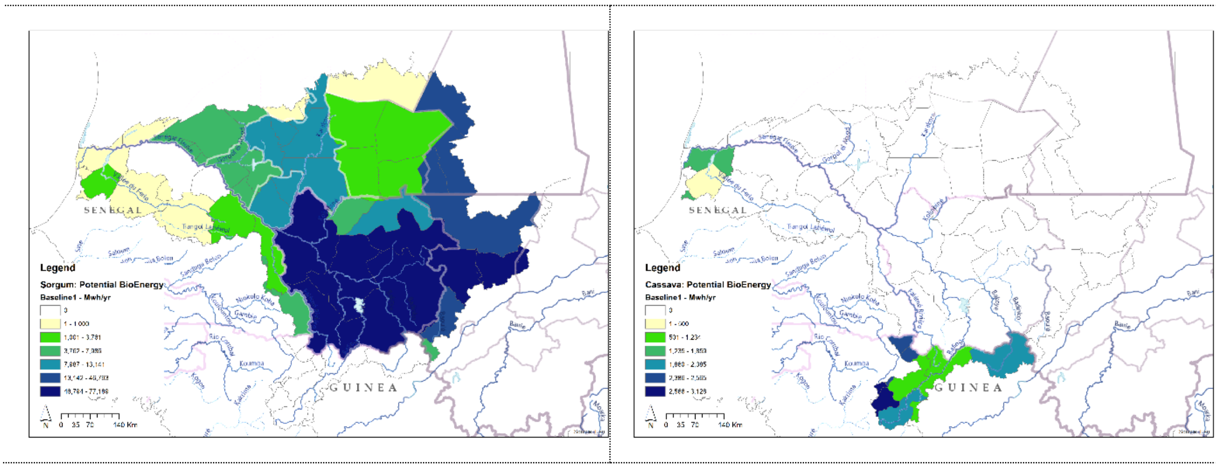
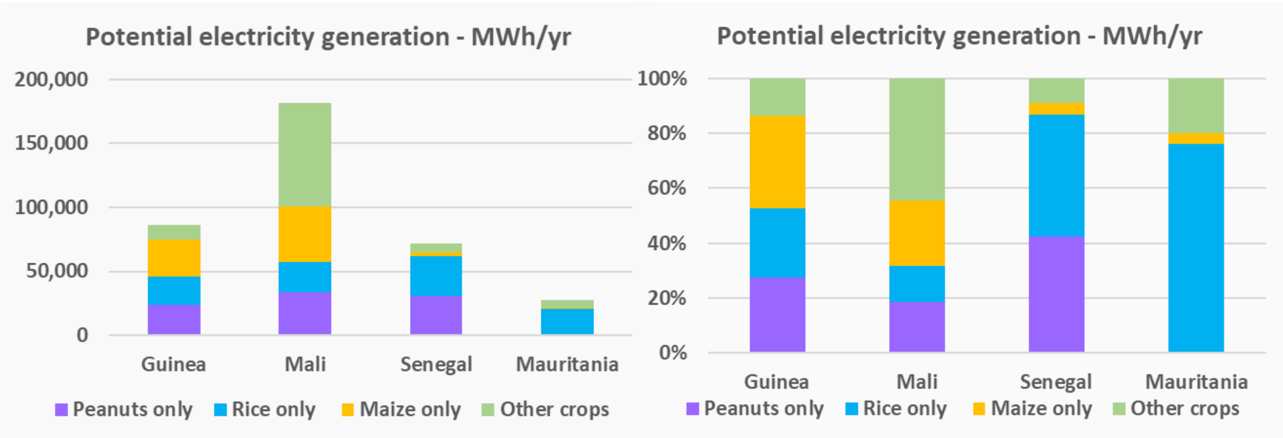


Figure 15. Potential electricity generation from residues for some dominant crops in the 4 countries of the Senegal river basin



4.1.2 Crop management scenarios

After the estimation of the crops residues capacity for bioenergy production in the SRB, this productivity can also be optimized in specific regions and/or to reduce the total cost and the efforts to obtain this energy. To this scope, different scenarios have to be tested and analysed to finally identify optimized strategies. Indeed several options need to be considered in order to support the potential spread of bioenergy resource all over the river basin: it should be possible to identify which crops consider, in which regions the bioenergy is more effective and which strategy. In a first approach the bioenergy yield potential at river basin level, can be increased simply by i) changing the pattern of crops cultivated, ii) increasing agricultural yield productivity of crops, in particular those with a better energetic potential, or iii) by a combination of the two strategies.

To select which crop would bring the major benefit, the developed model would allow to take into account how different crop allocation and different productivity levels would impact such production. This is supporting the optimisation of these strategies to find the most efficient solution to have more food crop production and more energetic potential. In the Senegal river basin it is clear that one of the most sensitive parameter is yield productivity, as in most of the cases the level of productive is far to be optimized and can realistic be improved with the adoption of best management practices. indeed, it's true that crop yield productive improvement is not an easy task, specifically at regional level, but it may be easier to focus the adoption of the improved strategies just in specific regions, where bioenergy is more required: these regions of focus can be identified by end users and in general by developing planning tools but would correspond to areas where it's more difficult to bring standard energy sources and where the presence of small farming systems can benefit more by the adoption of such bioenergy plants.

Analysis of results for bioenergy estimation by predefined crop management scenarios

In this section an analysis of the impact of different management of crop land and crop production is provided. In order to have an example of the impact of different strategies, five standards scenarios were considered. These scenarios have been already described in the methodological section, anyway we summarize their most important characteristics and focus:

- Change of crop areas without affecting total cropland or cropping intensity: these are the results of user defined crop allocation input;
- Change of crop yield productivity by improving the management of specific (end user selection) crops
- Combination of the previous strategies

In order to compare the different scenarios, the output energy production for each crop is compared and also the potential use of this energy is assessed: to this scope the energy household demand satisfaction and the water irrigation energy demand potential satisfaction are estimated. Results for baseline scenarios and others are compared in the following Table 10. In this summary table, for each scenario are reported:

- The main parameters forcing the scenario: for example, for the scenario *Area.1*, the assessed strategy is to increase the cropping surface for peanuts, while reducing other crops (ex of forcing parameter: increase of only peanuts area by 20%).
- The bioenergy electricity production potential capacity: here expressed at monthly temporal scale for all crop residues or for specific crops (in the table just peanuts, rice and maize are reported)
- The relative percentage changes in cropland distribution compared with the baseline (in green colour when there is an increase of the area of production, in red if there is a decrease)
- The balance between energy production and energy use is also estimated and in the last part of the table the saved energy is estimated by assuming all crop are potentially irrigated, all population household demand for 2016 of for 2025 is satisfied: when the percentage is negative this means it is not possible to satisfy all energetic demand even assuming all crop residues are used.

Table 10. Potential electricity generation from crop residue at river basin level: comparison between different scenarios and impact on irrigation and household demands for 2016 and 2025.

Scenario code	***Main parameters***	***Monthly Electrivity yields (MWh/month)***				***Changes %***				***Saving energy for other uses***		
	Avg factors Residues use (70%-50%)	All crops	Peanuts only	Rice only	Maize only	All crops	Peanuts only	Rice only	Maize only	with irrigation demand 100%	with urban demand 2016 100% satisfied	with urban demand 2025 100% satisfied
Baseline.1 - Avg factors		367,421	88,234	98,084	76,928					51%	17%	-4%
Area.1 - Avg factors	peanuts: sup. +20%	372,569	105,881	94,705	72,533	1.4	20.0	-3.4	-5.7	52%	18%	-3%
Area.2 - Avg factors	rice: sup.+20%	378,626	84,729	117,700	74,021	3.0	-4.0	20.0	-3.8	51%	18%	-3%
Area.3 - Avg factors	maize: sup.+20%	373,179	84,791	95,681	92,313	1.6	-3.9	-2.4	20.0	51%	18%	-3%
AreaYield-1 - Avg factors	maize: sup.&yield +20%	391,642	84,791	95,681	110,776	6.6	-3.9	-2.4	44.0	54%	22%	2%
Yield-1 - Avg factors	all: yield +20%	440,905	105,881	117,700	92,313	20.0	20.0	20.0	20.0	59%	31%	13%

Scenarios info:
Base.1 - Avg factors - Residues use (70%-50%) - Power Plant efficiency: 16%-CropArea():no change - pop. 2017 - HH energy demand UN Energy statistics 2016
Area.1 - Avg factors - Residues use (70%-50%) -Power Plant efficiency: 16%-CropArea(peanuts):+20% - pop. 2017 - HH energy demand UN Energy statistics 2016
Area.2 - Avg factors - Residues use (70%-50%) -Power Plant efficiency: 16%-CropArea(rice):+20% - pop. 2017 - HH energy demand UN Energy statistics 2016
Area.3 - Avg factors - Residues use (70%-50%) -Power Plant efficiency: 16%-CropArea(maize):+20% - pop. 2017 - HH energy demand UN Energy statistics 2016
2016
Yield-1 - Avg factors - Residues use (70%-50%) -Power Plant efficiency: 16%-Yields:+10% - pop. 2017 - HH energy demand UN Energy statistics 2016

The importance of crop land allocation is evident, but also it is strictly dependent on the objective. For example, by considering only energetic potential increase as objective, according to the proposed scenarios, it is more efficient to use more cropland for rice cropping system while reducing other crops, as this would bring to an increase of energy production of about 3% (see **Errore. L'origine riferimento non è stata trovata.**). Anyway several aspect need to be considered when introducing a change of cropland allocation: such as for example the local need of specific crop for food demand, the difficult to replace cropping system already established, the potential suitability for local specific crops, the economic cost and market demands for crops, etc. . For this reason these scenarios has to be considered just as examples to show the potential impact on bioenergy: a more focused selection would potentially be possible with i) local expert inputs and ii) multiobjective optimization tools, as presented later.

Concerning the irrigation demand, It is interesting to note that given the high potential of energetic production, it is potentially possible to use all the energy produced to sustain the energetic demand for all crops: this clearly assuming that water is available, nearby to the fields, and with limited depth for the water pumping cost. Indeed, this estimation is just to underline how this technology can be used to facilitate the irrigation pumping in rural areas, while a water accounting balance and a cost analysis would be finally required. The results of this estimation is that energy is technical available to pump water for irrigation, but still an economic assessment is needed.

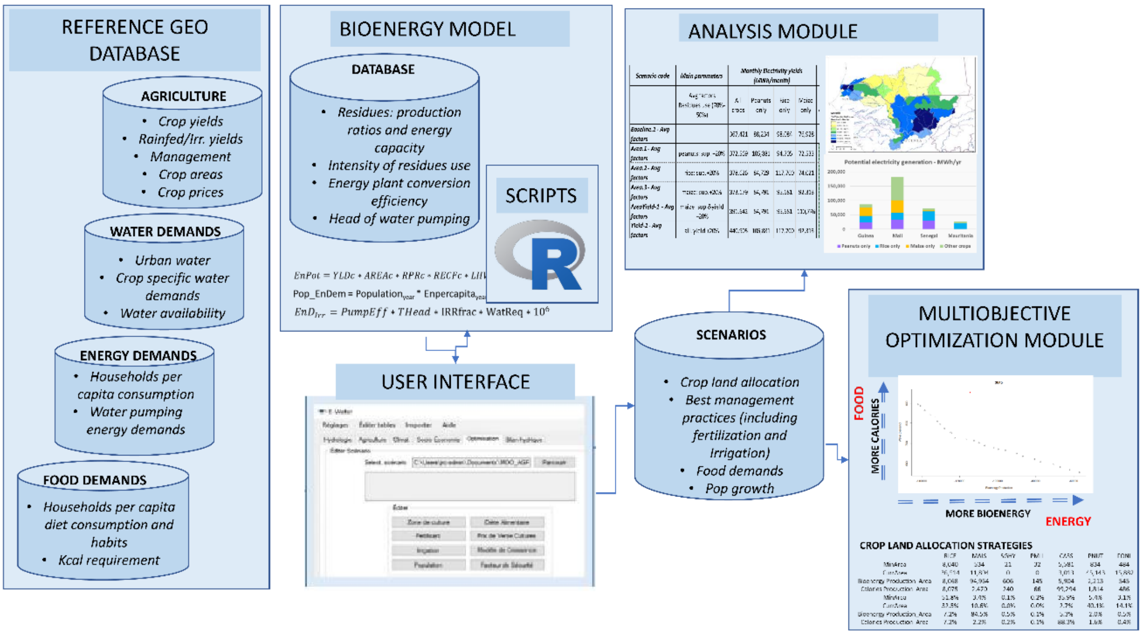
Assuming energy is fully produced and used for water pumping to irrigated land, still a quote of energy is available to satisfy households energetic demand. This energy is no more sufficient if considering increasing population density and per capita energy demand (because of new habits, life quality, etc.): basically all the scenarios have negative values for saved energy for household demands in 2025 (see **Errore. L'origine riferimento non è stata trovata.**).

This preliminary analysis clearly shows an high potentially of bioenergy resource in the Senegal river basin that, given also the limited current energetic demand from population, would potentially allow to satisfy all required need.

4.2 Multi-objective optimization solutions for Bioenergy

The aim of this application is to assess how local agricultural crop residues may potentially sustain local energy demand from several sectors, but specifically from household energy demand and irrigation energy demand for water pumping and movement. This assessment requires the consideration of different objectives that can be contrasting and difficult to be balanced. In doing so, we need to deal with the following issues: (1) multiple crop specific residues productivity (2) multiple crop specific residues energy capacity (2) limited resources for crop management improvement (such as fertilizers and irrigation) and (3) variable household demands. To that purpose a Multi Objective Optimization (MOO) tool integrating regional data and the energetic model was developed.

Figure 16 Schematic representation of Bioenergy model and the Nexus multiobjective module



4.2.1 Bioenergy from crop residues and the WEFE Nexus

The aim of such a system is to assess the bioenergy productivity in the Senegal river basin in a WEFE Nexus context. More specifically the bioenergy model is aimed to be able to take into account different objectives (Nexus objectives or objectives linked with different Nexus components), usually contrasting objective and to identify optimal solutions allowing end users for the identification of the most suited trad off across the sectors. This is a bioenergy module so not all WEFE Nexus components are necessary pertinent, nevertheless we can summarize here the different components involved:

ENERGY: this is clearly the most important WEFE component of interest of this analysis. More specifically the Energy is here considered as the potential energy coming from a renewable source such as crop residues. Indeed this component and it's development would directly affect other components such as the Environment (bioenergy resource), the social (impact of livehood of small household, impact positive and/or negative on food diets), the Food component (as any crop land allocation would impact food distribution) and the Water as impacting potentially the water use and balance.

FOOD: The food component is considered in this assessment by taking into account the crop land allocation and the agricultural management practices affecting the yields specific productivity and the global production of food items. Food local demand is indeed considered in this assessment as a constraint: this means that all identified strategies with different trade off should always ensure enough food to satisfy local demands (no consideration about import/export of products between countries and regions)

ENVIROMENT: In this assessment there is any specific objective to be minimize and/or maximized related to the environment but: the constraint to not increasing cropland is indeed finalised to reduce the impact on land occupation and clearing; in addition the capability to increase the use of bioenergy would reduce the need for wood-fuel thus limiting one of the main impacting activity for deforestation and soil erosion in the area: in this sense a post analysis would allow to consider an objective as the quantity of wood fuel required.

WATER: In this assessment water component is mainly considered as its quantity and availability. Mainly the link with the water component is by the consideration of water requirement for specific crop. In this approach water use is a minimization objective: all the management solutions are aimed to maximize energy production, while ensuring food needs and minimizing and limiting water consumptions.

4.2.2 Analysis of results

In this section, we present an example application of the optimization tool in the context of bioenergy production in the SRB. Our main aim is to forecast the impact of different cropland allocation, by assuming that current local food demand is satisfied. A preliminary assessment was performed in order to flag specific regions where currently, given the current management strategies and land management, it is not possible to satisfy with local production food demand (Table 11): this indicator is just linked with food infeasibility of local production capacity, but does not necessarily imply that there is a food safety issue in the region as commodities product can be also "imported" by neighbouring regions and eventually at the market. Anyway is a good indicator for the identification of regions that would benefit of specific strategies. So in this study we assume that food crops cannot be traded between regions or countries, as the goals is to assess the tradeoff between energy production and food self sufficiency. Besides, the focus is for small farmers, who aim to cover their own subsistence, or to sell the excess in local markets. In addition, limited road infrastructures and poor market organization would tend to further decrease the possibility of such exchange.

Table 11. Food demand satisfaction by specific local production capability, under current management as available for 2016.

Country	*Region*	*Rice*	*Mais*	*Sorgum*	*Millet*	*Tubers*	*Peanuts*	*OtherCereals*
Guinea	Dabola	15.8%	4.1%	no prod.	no prod.	23.3%	2.3%	4.0%
	Dinguiraye	19.4%	2.0%	no prod.	no prod.	32.5%	3.9%	7.5%
	Siguiri	115.2%	9.7%	no prod.	no prod.	65.1%	22.1%	117.2%
	Koubia	13.7%	0.3%	no prod.	no prod.	2.1%	1.8%	0.2%
	Labé	116.3%	1.4%	no prod.	no prod.	8.8%	12.1%	1.8%
	Mali	0.9%	0.1%	no dem.	no prod.	0.3%	0.2%	0.1%
	Tougué	113.0%	9.6%	no prod.	no prod.	56.6%	41.2%	7.0%
	Dalaba	88.2%	4.6%	no prod.	no prod.	18.5%	19.0%	6.0%
	Mamou	88.2%	12.6%	no prod.	no prod.	44.8%	27.0%	8.0%
Mali	Bafoulabé	359.5%	64.5%	29.1%	2493.4%	no prod.	13.5%	26756.5%
	Diéma	no prod.	609.4%	33.5%	73.0%	no prod.	36.6%	no prod.
	Kayes	6477.1%	82.1%	87.9%	1693.4%	no prod.	30.0%	no prod.
	Kéniéba	215.0%	27.6%	29.6%	no prod.	no prod.	6.3%	no prod.
	Kita	1251.6%	68.1%	51.4%	371.9%	no prod.	7.6%	no prod.
	Nioro	no prod.	1254.9%	144.6%	6.5%	no prod.	62.4%	no prod.
	Yélimané	no prod.	328.6%	239.7%	5603.3%	no prod.	13.8%	no prod.
	Banamba	658.1%	28.8%	23.7%	17.5%	no prod.	6.2%	86.0%
	Kangaba	7.0%	5.4%	32.2%	287.5%	no prod.	0.9%	no prod.
	Kati	38.3%	7.8%	22.4%	89.1%	no prod.	6.6%	no prod.
	Kolokani	1856.7%	42.4%	21.1%	52.4%	no prod.	5.3%	no prod.

Country	Region	Rice	Mais	Sorgum	Millet	Tubers	Peanuts	OtherCereals
	Nara	no prod.	145.1%	37.3%	71.7%	no prod.	33.9%	no prod.
	Ségou	0.1%	1.4%	0.4%	0.1%	no prod.	0.5%	0.1%
Senegal	Saraya	104.6%	21.9%	7.0%	no prod.	no prod.	6.5%	no prod.
	Kébémer	no prod.	no prod.	10.2%	0.1%	0.0%	0.0%	no dem.
	Linguère	no prod.	391.9%	573.2%	38.7%	no prod.	8.8%	no prod.
	Louga	no prod.	no prod.	476.5%	34.6%	120.4%	5.5%	no prod.
	Kanel	no prod.	8300.1%	91.0%	93.6%	no prod.	392.3%	no prod.
	Matam	101.6%	no prod.	no prod.	no prod.	no prod.	no prod.	no prod.
	Ranérou Ferlo	no prod.	147.1%	24.5%	23.4%	no prod.	31.1%	no prod.
	Dagana	13.9%	572.5%	1404.4%	8140.0%	10.6%	31.7%	no prod.
	Podor	106.6%	no prod.	no prod.	16012.7%	no prod.	no prod.	no prod.
	Saint-Louis	8.9%	no prod.	1.8%	140.0%	no prod.	0.4%	no dem.
	Bakel	1072.9%	52.8%	28.5%	287.1%	no prod.	84.7%	no prod.
	Goudiry	no dem.	no dem.	no dem.	no dem.	no dem.	no dem.	no dem.
Mauritania	Assaba	no prod.	116.2%	91.5%	no prod.	no prod.	no prod.	no prod.
	Brakna	108.3%	74.3%	107.2%	166.4%	no prod.	no prod.	no prod.
	Gorgol	181.1%	39.5%	153.3%	366.8%	no prod.	no prod.	no prod.
	Guidimaka	3347.9%	129.9%	73.8%	719.2%	no prod.	no prod.	no prod.
	Hodh ech Chargui	no prod.	1437.8%	15.7%	12.5%	no prod.	no prod.	no prod.
	Hodh el Gharbi	no prod.	415.4%	211.8%	4045.1%	no prod.	no prod.	no prod.
	Tagant	no prod.	20.1%	12.9%	no prod.	no prod.	no prod.	no prod.
	Trarza	4.0%	431.2%	1312.4%	no prod.	no prod.	no prod.	no prod.
	Guinea	55.3%	4.2%	no prod.	no prod.	24.5%	10.8%	4.5%
	Mali	104.9%	48.9%	39.8%	36.9%	no prod.	10.9%	128.6%
	Senegal	72.3%	297.8%	123.0%	62.3%	39.2%	13.9%	no prod.
	Mauritania	49.1%	90.7%	83.2%	150.8%	no prod.	no prod.	no prod.

This analysis highlight that in many cases local production for specific food agricultural products is totally absent or not able to completely satisfy the current food demand by population living in the region (including urban and rural population). For example if we look at Table 11 we can observe:

- Several crops have a over production (green colour) as evident for example in Guinea for Mazie, cereals, and peanuts;
- Other crops are no produced at all (no prod.) or have significative negative balance (se for example red spots for rice in Mali regions);
- At country level (summury of the availability and demands) these missing quantities partially disappears everywhere except for some specific crops in some specific country: for example for dry cereals (sorghum and millet) in Guinea or for maize in Senegal.

As these missing quantities generally disappear at country level (within the river basin), in order to introduce a constraint in the optimization process, we set the minimum requirement for each food crop to be produced without allowing that required food demand area would be higher then the available cropland. This would bring to some regions where infectibility persist, but this is also linked with capability, and technical feasibility of each region.

In addition, users can use the optimization tool to search for optimal tradeoff solution between bioenergy and food production by aggregating specific region: for example, in Guinea, Siguiri region has negative balance for rice, but just considering the neighbouring region of Dinguiraye this negative value turns to positive.

In the optimization process several objectives can be optimized simultaneously; this is a key capability of the approach, but it should be also pointed out that the concurrent use of more objective can make more complex the interpretation of the results. Indeed the easiest way to analyse optimized results is by means of Pareto front graphics where for each solution the resulting score for the optimized objectives is showed and these graphics can be easily analysed in a 2D dimensional way, while moving to 3D and more it’s not suggested.

The first analysis of optimization performed consider the need to analysis the bioenergy production in a WEFE Nexus context. To this scope the following indicators, objectives and constraints (Table 12) have been chosen:

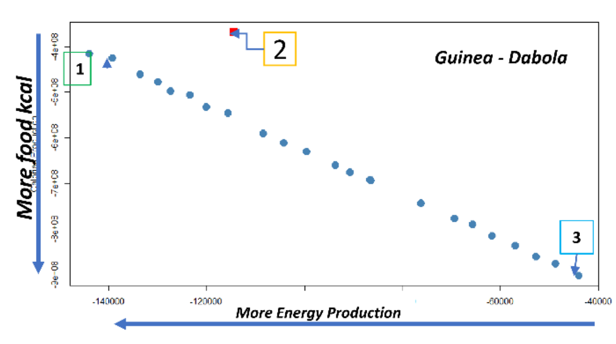
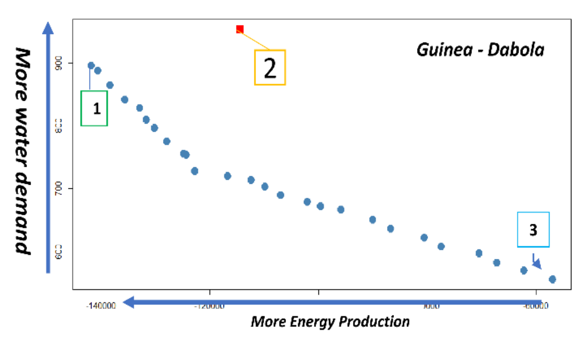
Table 12. List of WEFE Nexus component and related objectives for the optimization of bioenergy production in the Senegal river basin.

NEXUS	OBJECTIVE	TYPE	AIM	USED
ENERGY	Total bioenergy potential	MOO Objective	Maximize	*v*
FOOD	Food crop production	MOO Objective	Maximize	*v*
WATER/**E**NVIRONMENT	Water demands	MOO Objective	Minimize	*v*
FOOD/**E**NVIROMENT	Food demands	MOO Constraint	Minimum threshold	*v*
WATER/**E**NVIRONMENT/FOOD	Residues for Livestock feed demand	MOO Objective	Maximize	*v*
ENERGY	Pumping water energy	MOO Objective	Minimize	
WATER/**E**NVIRONMENT	Best management: optimal water and fertilizer manag.	MOO Objective	Minimize	

Errore. L'autoriferimento non è valido per un segnalibro. shows Pareto frontier, formed by trade off efficient strategies between the selected WEFE objectives and the capacity to produce bioenergy from crop residues. As showed in the figures, both objectives can be significantly increased or reduced depending on the combination of cropland allocation.

In the following Table 13, just 2 solutions are reported in order to briefly show how different strategies can affect bioenergy production and the Nexus objective. These two solutions are the ones opposite (Top left and bottom right) in the Pareto maximizing one of the two optimized objectives. It is also reported the solution corresponding to the current cropland distribution (red square) to highlight the difference with optimized solutions.

Figure 17. Example of Optimization Pareto solutions for Dabola region in Guinea as resulting by two different set of optimization objectives: 1) focus on Food and bio-Energy tradeoff 2) focus on Water demand and bio-Energy tradeoff.

Pareto-WEFE Nexus Objectives: Food vs Energy	*Pareto-WEFE Nexus Objectives: Water vs Energy*
	

In this specific region, corresponding to the administrative unit of Dabola (3045) in Guinea, there is quite high cropland availability compared with local food demand (for example rice surplus is about 85%, as derived by Table 11):

- This allows various solutions for the optimization of land area, while producing at the same time enough food (local satisfaction. The food constraint is not limiting the variability of solutions, as it can be easily ensured.
- Indeed if we look at the first optimization Pareto set of solutions (FOOD vs Energy): a wide range of different solutions is possible; Rice crop is replaced as it allows maintaining a minimum requirement (8000 ha with current productivity), and it is reduced to about 7% of cropland for the 2 extreme solutions. Mais is used mainly for energy solution (n. 1 in the Pareto) (84% of cropland), as it produces much more energy residues), while for calories solution (n. 2 in the Pareto) the most used crop in this region would be the Cassava (for about 88% of crop land) as this crop has the highest potential for production (because of higher yields) of food calories.
- In the second optimization Pareto (WATER vs Energy) the cropland allocation is different: for rice there is the same solution, while tubers are not much reduced and replaced by mais and cereals and some peanuts. In this case the water requirements is the driving variable and for this reason cereals, better growing with limited amount of water, are preferred.
- It is interesting to note that both optimization scenarios result basically in the same level of bioenergy potential production: about 140 000 MWh7yr. This has to be expected as bioenergy production is a common maximization objective. Also with a different set of optimization objectives mostly the same max quantity (+26% and +24%) of bio energy can be reached (indeed this is a common opt. obj). The opposite solutions for FOOD and Water demand corresponds indeed at a decreasing of bioenergy production (vs current baseline) of -62% and -50%.

Table 13. Example of output results of the optimization for two setup of the MOO in the administrative unit of Dabola in Guinea.

Scenario	Solution	Description	Unit	Rice	Mais	Sorghum	Millet	Tubers	Peanuts	Cereals
Constraint	Fixed	Food mimimum areas constraint	ha	8,040	534	21	32	5,581	834	484
Current	Current	cropland allocation	ha	36,514	11,894	0	0	3,013	45,143	15,882

Scenario	Solution	Description	Unit	Rice	Mais	Sorghum	Millet	Tubers	Peanuts	Cereals
Current	Current	cropland allocation	%	32.50%	10.60%	0.00%	0.00%	2.70%	40.10%	14.10%
FOOD vs Energy	Sol 1 (Max Energy)	cropland allocation	ha	8,068	94,964	606	145	5,904	2,213	545
	Sol 3 (Max Food)	cropland allocation	ha	8,075	2,470	240	66	99,294	1,814	486
	Sol 1 (Max Energy)	cropland allocation	%	7.20%	84.50%	0.50%	0.10%	5.30%	2.00%	0.50%
	Sol 3 (Max Food)	cropland allocation	%	7.20%	2.20%	0.20%	0.10%	88.30%	1.60%	0.40%
WATER vs Energy	Sol 1 (Max Energy)	cropland allocation	ha	8,044	84,244	182	73	5,604	13,577	721
	Sol 3 (Min Water dem.)	cropland allocation	ha	8,042	920	305	37	11,710	10,571	80,861
	Sol 1 (Max Energy)	cropland allocation	%	7.20%	74.90%	0.20%	0.10%	5.00%	12.10%	0.60%
	Sol 3 (Min Water dem.)	cropland allocation	%	7.20%	0.80%	0.30%	0.00%	10.40%	9.40%	71.90%

Scenario	Solution	Bioenergy	Water demand	Pumping energy	Food Kcal production
		MWh/yr	*m3/yr*	*MWh/yr*	*Kcal/yr*
Current	Current	114,458	953	84,321	368,364,463
FOOD vs Energy	Sol 1 (Max Energy)	143,916	916	81,087	416,103,973
	Sol 3 (Max Food)	43,972	545	48,201	902,472,089
	Sol 1 vs Current	25.7%	-3.9%	-3.8%	13.0%
	Sol 3 vs Current	-61.6%	-42.8%	-42.8%	145.0%
WATER vs Energy	Sol 1 (Max Energy)	141,834	895	79,195	412,504,106
	Sol 3 (Min Water dem.)	56,882	556	49,180	308,741,626
	Sol 1 vs Current	23.9%	-6.1%	-6.1%	12.0%
	Sol 3 vs Current	-50.3%	-41.7%	-41.7%	-16.2%

In Figure 18 and

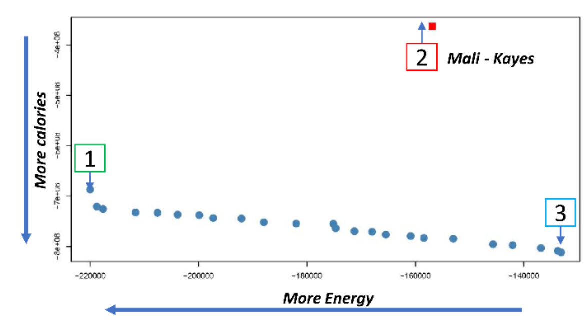
Table 14 Pareto frontier and cropland allocation solutions for the region of Kayes in Mali are showed. It can be observed:

- by considering food vs energy: sorghum crop would need to be replaced by rice and tubers in order to increase the capability to produce more food kcal while ensuring minimum quantity to sustain local food demands. It must be stressed that these distribution are clearly linked with the current productivity capacity of each crop. To maximize energy for example rice is dominating with a percentage of about 55%, while for maximizing food (n.3) tubers are dominant (42%).

- In the second optimization Pareto (WATER vs Energy) the cropland allocation is different: rice is not increased more than the minimum required quantity for food diet, while Mais (for energy) and tubers and dry cereals (such as Fonio) are much more used for maximizing food while preserving water.
- both optimization scenarios result basically in the same level of bioenergy potential production: about 220 000 MWh/yr, correspondent to an increase of bioenergy of about 40% compared to current condition. The opposite solutions for FOOD and Water demand corresponds indeed at a decreasing of bioenergy production (vs current baseline) of -15% and -50%.

Figure 18. Example of Optimization Pareto solutions for Kayes region in Mali as resulting by two different set of optimization objectives: 1) focus on Food and bio-Energy tradeoff 2) focus on Water demand and bio-Energy tradeoff.

Pareto-WEFE Nexus Objectives: Food vs Energy	***Pareto-WEFE Nexus Objectives: Water vs Energy***



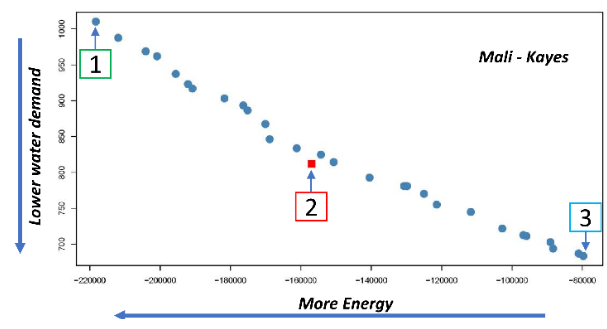


Table 14. Example of output results of the optimization for two setup of the MOO in the administrative unit of Kayes in Mali.

Scenario	Solution	Description	Unit	Rice	Mais	Sorghum	Millet	Tubers	Peanuts	Cereals
Constraint	Fixed	Food mimimum areas constraint	ha	12,305	6,954	6,141	9,277	1,196	898	230
Current	Current	cropland allocation	ha	482	34,028	66,611	2,844	0	19,375	0
Current	Current	cropland allocation	%	0.4%	27.6%	54.0%	2.3%	0.0%	15.7%	0.0%
FOOD vs Energy	Sol 1 (Max Energy)	cropland allocation	ha	68,454	36,656	6,154	9,359	1,283	1,056	377
	Sol 3 (Max Food)	cropland allocation	ha	47,304	7,160	6,154	9,591	51,731	1,127	273
	Sol 1 (Max Energy)	cropland allocation	%	55.5%	29.7%	5.0%	7.6%	1.0%	0.9%	0.3%
	Sol 3 (Max Food)	cropland allocation	%	38.4%	5.8%	5.0%	7.8%	41.9%	0.9%	0.2%
WATER vs Energy	Sol 1 (Max Energy)	cropland allocation	ha	12,488	88,371	6,165	9,559	1,593	3,483	1,681
	Sol 3 (Min Water dem.)	cropland allocation	ha	12,555	7,141	6,732	9,347	40,483	1,919	45,164
	Sol 1 (Max Energy)	cropland allocation	%	10.1%	71.6%	5.0%	7.8%	1.3%	2.8%	1.4%

Scenario	Solution	Description	Unit	Rice	Mais	Sorghum	Millet	Tubers	Peanuts	Cereals
	Sol 3 (Min Water dem.)	cropland allocation	%	10.2%	5.8%	5.5%	7.6%	32.8%	1.6%	36.6%

Scenario	Solution	Bioenergy	Water demand	Pumping energy	Food Kcal production
		MWh/yr	*m3/yr*	*MWh/yr*	*Kcal/yr*
Current	Current	156,904	812	71,858	363,322,638
FOOD vs Energy	Sol 1 (Max Energy)	220,011	1,358	120,153	686,703,116
	Sol 3 (Max Food)	133,133	1,029	91,047	811,482,944
	Sol 1 vs Current	40.2%	67.2%	67.2%	89.0%
	Sol 3 vs Current	-15.2%	26.7%	26.7%	123.4%
WATER vs Energy	Sol 1 (Max Energy)	218,312	1,010	89,397	598,790,835
	Sol 3 (Min Water dem.)	79,749	683	60,487	596,263,833
	Sol 1 vs Current	39.1%	24.4%	24.4%	64.8%
	Sol 3 vs Current	-49.2%	-15.8%	-15.8%	64.1%

In Table 15 and Figure 19 Pareto frontiers and cropland allocation solutions for the region of Louaga (5178) in Senegal are showed. It can be observed:

- by considering food vs energy: millet and peanuts would be replaced by rice and tubers in different percentages depending on the objective of the optimization: for energy rice is dominant while for food tubers are dominant.
- In the second optimization Pareto (WATER vs Energy) the cropland allocation is different: still rice is much increased, but also maize and tubers are relatively important. Also some peanuts are maintained.
- Food vs energy scenario results with the highest bioenergy potential production: about 360 000 MWh/yr, correspondent to an increase of bioenergy of about 140% compared to current condition. The opposite solutions for FOOD and Water demand corresponds indeed at an increasing of energy for the first case (+35%) and at a decreasing of bioenergy production (vs current baseline) of -13% for the second case.

Figure 19. Example of Optimization Pareto solutions for Louga region in Senegal as resulting by two different set of optimization objectives: 1) focus on Food and bio-Energy tradeoff 2) focus on Water demand and bio-Energy tradeoff

Pareto-WEFE Nexus Objectives: Food vs Energy	***Pareto-WEFE Nexus Objectives: Water vs Energy***

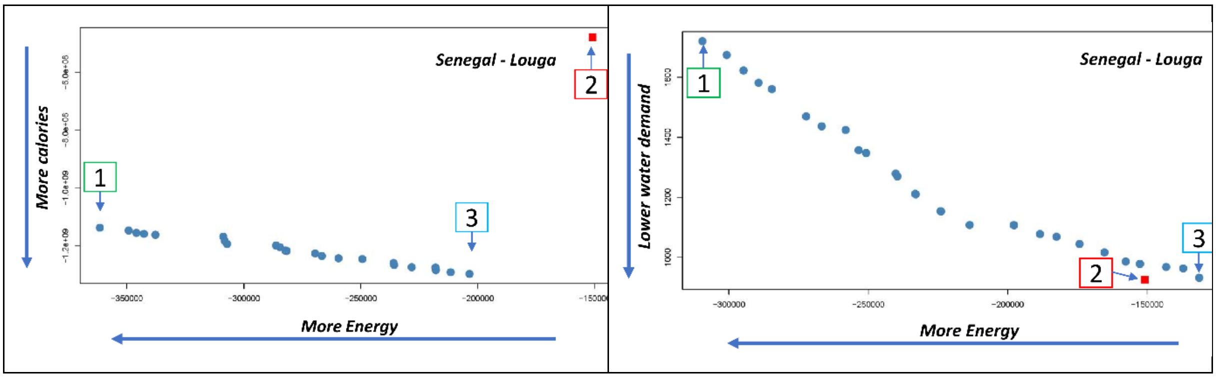


Table 15. Example of output results of the optimization for two setup of the MOO in the administrative unit of Louga in Senegal.

Solution	Description	Unit	Rice	Mais	Sorghum	Millet	Tubers	Peanuts	Cereals
Fixed	Food mimimum areas constraint	ha	17,288	4,539	1,112	3,221	2,004	1,556	14
Current	cropland allocation	ha	0	0	1,946	45,743	616	106,072	0
Current	cropland allocation	%	0.0%	0.0%	1.3%	29.6%	0.4%	68.7%	0.0%
Sol 1 (Max Energy)	cropland allocation	ha	140,744	4,709	1,354	3,263	2,039	2,138	130
Sol 3 (Max Food)	cropland allocation	ha	67,125	4,650	1,250	3,310	76,108	1,853	81
Sol 1 (Max Energy)	cropland allocation	%	91.2%	3.1%	0.9%	2.1%	1.3%	1.4%	0.1%
Sol 3 (Max Food)	cropland allocation	%	43.5%	3.0%	0.8%	2.1%	49.3%	1.2%	0.1%
Sol 1 (Max Energy)	cropland allocation	ha	90,322	39,471	1,309	5,870	2,541	13,713	1,151
Sol 3 (Min Water dem.)	cropland allocation	ha	17,995	22,291	2,690	7,507	89,280	12,450	2,163
Sol 1 (Max Energy)	cropland allocation	%	58.5%	25.6%	0.8%	3.8%	1.6%	8.9%	0.7%
Sol 3 (Min Water dem.)	cropland allocation	%	11.7%	14.4%	1.7%	4.9%	57.8%	8.1%	1.4%

Scenario	Solution	Bioenergy	Water demand	Pumping energy	Food Kcal production
		MWh/yr	*m3/yr*	*MWh/yr*	*Kcal/yr*
Current	Current	150,906	925	81,864	478,144,622
FOOD vs Energy	Sol 1 (Max Energy)	361,557	2,057	182,069	1,136,843,710
	Sol 3 (Max Food)	203,489	1,320	116,836	1,296,762,229

Scenario	Solution	Bioenergy	Water demand	Pumping energy	Food Kcal production
	Sol 1 vs Current	139.6%	122.4%	122.4%	137.8%
	Sol 3 vs Current	34.8%	42.7%	42.7%	171.2%
WATER vs Energy	Sol 1 (Max Energy)	309,505	1,720	152,255	939,016,066
	Sol 3 (Min Water dem.)	131,366	932	82,474	1,170,173,508
	Sol 1 vs Current	105.1%	86.0%	86.0%	96.4%
	Sol 3 vs Current	-12.9%	0.7%	0.7%	144.7%

In Figure 20 and Table 16**Errore. L'origine riferimento non è stata trovata.** Pareto frontiers and cropland allocation solutions for the region of Gorgol (6005) in Mauritania are showed. It can be observed:

- In the case of Food vs Energy scenario only one solution is found as optimal both for maximizing energy and food: this is because of the high difference of productivity reported in the region for the cropping system. Indeed rice is reported to produce more than 5 tons/ha while all other crops are below 1. With this input and parameterization clearly rice is the only solution optimal from a mathematical point of view. Anyway it is not realistic to propose an increase of rice to cover all cropland.
- Indeed this is also evident by the second scenario with the optimization Water vs Energy: in this case for example rice is increased just to 22% (current is 14%) of cropland, in order to limit water demand. Other important crops selected with the optimization and not used under current land management are: dry cereals (such as Fonio), tubers (such as cassava and yam)
- Food vs energy scenario results with the highest bioenergy potential production: about 94 000 MWh/yr, correspondent to an increase of bioenergy of about 225% compared to current condition. The opposite solutions for FOOD and Water demand corresponds indeed to a level of bioenergy equal to the current one (see red point in Figure 20 - right).

Also crop management is an important aspect to be considered. Indeed for example by changing level of productivity for the crops, very different optimized solutions would be identified. For example, by introducing a "better management" for maize a new pareto is estimated (see

- Figure 21) where cropland allocation is more diversified and the optimization tool is more able to play and propose diversified solutions.

Figure 20. Example of Optimization Pareto solutions for Gorgol region in Mauritania as resulting by two different set of optimization objectives: 1) focus on Food and bio-Energy tradeoff 2) focus on Water demand and bio-Energy tradeoff.

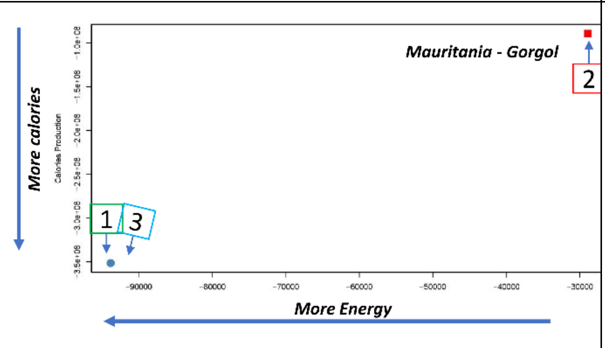
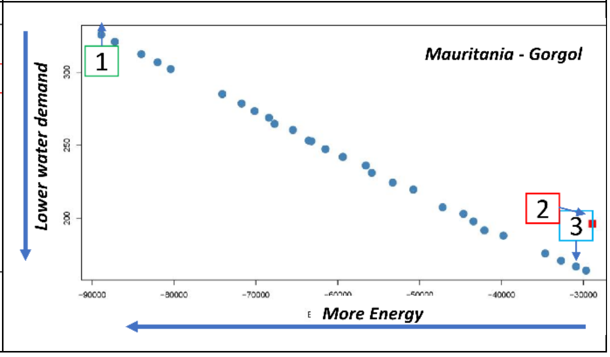
Pareto-WEFE Nexus Objectives: Food vs Energy	*Pareto-WEFE Nexus Objectives: Water vs Energy*
	

Table 16. Example of output results of the optimization for two setup of the MOO in the administrative unit of Gorgol in Mauritania.

Scenario	Solution	Description	Unit	Rice	Mais	Sorghum	Millet	Tubers	Peanuts	Cereals
Constraint	Fixed	Food mimimum areas constraint	ha	5,526	336	1,529	66	61	42	64
Current	Current	cropland allocation	ha	3,603	7,386	13,841	593	0	0	0
Current	Current	cropland allocation	%	14.2%	29.1%	54.4%	2.3%	0.0%	0.0%	0.0%
FOOD vs Energy	Sol 1 (Max Energy)	cropland allocation	ha	23,312	338	1,533	67	62	43	68
	Sol 3 (Max Food)	cropland allocation	ha	23,312	338	1,533	67	62	43	68
	Sol 1 (Max Energy)	cropland allocation	%	91.7%	1.3%	6.0%	0.3%	0.2%	0.2%	0.3%
	Sol 3 (Max Food)	cropland allocation	%	91.7%	1.3%	6.0%	0.3%	0.2%	0.2%	0.3%
WATER vs Energy	Sol 1 (Max Energy)	cropland allocation	ha	21,824	347	1,546	67	553	599	487
	Sol 3 (Min Water dem.)	cropland allocation	ha	5,629	403	1,535	123	7,979	622	9,131
	Sol 1 (Max Energy)	cropland allocation	%	85.8%	1.4%	6.1%	0.3%	2.2%	2.4%	1.9%
	Sol 3 (Min Water dem.)	cropland allocation	%	22.1%	1.6%	6.0%	0.5%	31.4%	2.4%	35.9%

Scenario	Solution	Bioenergy	Water demand	Pumping energy	Food Kcal production
		MWh/yr	*m3/yr*	*MWh/yr*	*Kcal/yr*
Current	Current	28,907	196	17,357	89,191,395
FOOD vs Energy	Sol 1 (Max Energy)	93,849	339	30,040	351,445,364
	Sol 3 (Max Food)	93,849	339	30,040	351,445,364
	Sol 1 vs Current	224.7%	73.1%	73.1%	294.0%
	Sol 3 vs Current	224.7%	73.1%	73.1%	294.0%
WATER vs Energy	Sol 1 (Max Energy)	88,904	326	28,828	336,303,838
	Sol 3 (Min Water dem.)	29,669	164	14,527	174,115,938
	Sol 1 vs Current	207.6%	66.1%	66.1%	277.1%
	Sol 3 vs Current	2.6%	-16.3%	-16.3%	95.2%

Figure 21. Example of Optimization Pareto solutions for Gorgol region in Mauritania: focus on Food and bio-Energy as resulting by two different set of crop yields productivity: 1) increase maize productivity 2) vs limit to rice production.

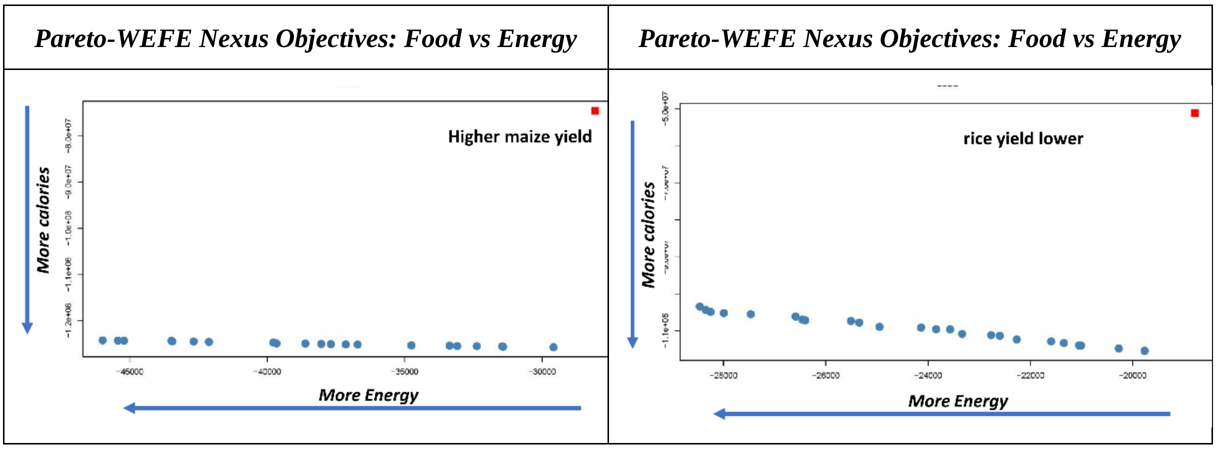


Table 17. Example of output results of the optimization for two setup of the MOO in the administrative unit of Gorgol in Mauritania as resulting by two different set of crop yields productivity: 1) increase maize productivity 2) vs limit to rice production.

Scenario	Solution	Description	Unit	Rice	Mais	Sorghum	Millet	Tubers	Peanuts	Cereals
Constraint	Fixed	Food mimimum areas constraint	ha	5,526	336	1,529	66	61	42	64
Current	Current	cropland allocation	ha	3,603	7,386	13,841	593	0	0	0
Current	Current	cropland allocation	%	14.2%	29.1%	54.4%	2.3%	0.0%	0.0%	0.0%
FOOD vs Energy - Higher Maize Yield	Sol 1 (Max Energy)	cropland allocation	ha	5,581	17,999	1,534	67	92	82	67
	Sol 3 (Max Food)	cropland allocation	ha	5,536	9,602	1,535	69	8,502	111	66
	Sol 1 (Max Energy)	cropland allocation	%	22.0%	70.8%	6.0%	0.3%	0.4%	0.3%	0.3%
	Sol 3 (Max Food)	cropland allocation	%	21.8%	37.8%	6.0%	0.3%	33.4%	0.4%	0.3%
FOOD vs Energy - Lower Rice Prod.	Sol 1 (Max Energy)	cropland allocation	ha	19,771	391	1,529	69	74	3,504	84
	Sol 3 (Min Water dem.)	cropland allocation	ha	14,064	369	1,529	84	8,846	454	76
	Sol 1 (Max Energy)	cropland allocation	%	77.8%	1.5%	6.0%	0.3%	0.3%	13.8%	0.3%
	Sol 3 (Min Water dem.)	cropland allocation	%	55.3%	1.5%	6.0%	0.3%	34.8%	1.8%	0.3%

5 Conclusions and discussion

The potential for electricity generation from crop residues resources from selected regions in the Senegal River Basin has been investigated in this study. The analysis focused on the assessment of crop residues valorisation in a WEFE Nexus context, by assessing the potential of use of such residues to support the production of electricity for small farms and to support at the same time other important need such as irrigation energy requirement, food self sufficiency and security, livestock and environment.

The technical analysis has shown that there is indeed an important potential to use these resources to generate electricity without impacting the other sectors involved. The assessment estimated the total production of residues available for transformation in about 7 M of tons in the Senegal river basin for the year 2016. Assuming the efficient exploitation of these residues to supply an ideal 600 kW cogeneration plant, the resulting energy efficiency potential for 2016 in the Senegal River basin was estimated approximately in 4.4 MWh per year. Energy electricity potential was estimated at subnational level allowing to regionally differentiate across the river basin areas where this technology can be more effectively introduced. At global scale it was observed that tice is the dominant crop for residues and energy generation both for Mauritania and Senegal: indeed these results can be associated with the Delta region of the river basin, where rice cropping intensity is higher. In Guinea, corresponding to the upper part of the basin also know as Fojuta Djallon region, the higher contribution comes from Maize crop. In Mali most diffused cropping systems as quantities are dry cereals and indeed the higher contribution is currently estimated from sorghum and maize. Another important cropping system contributing at river basin scale (for all riparian countries except Mauritania) is groundnuts (peanuts). Concerning spatial distribution of energy availability this is more concentrated in the Kayes area in Mali while for other regions it is much more regionally distributed along the main valley. The spatial identification is important as allows to identify energy strategy that can be realistically applied in rural areas, without requiring important movement, transport and storage of residues for such small installations.

In addition to this preliminary assessment, an analysis focused on the inclusion of WEFE Nexus concept has been developed. The aim of this analysis was to assess how local agricultural crop residues may potentially sustain local energy demand from several sectors, but specifically including the valuation of other objectives and aspect strictly or someway inter linked that can be contrasting (to the use and maximization of residues use for energy production) and difficult to be balanced (aspect linked with different WEFE components Energy, Water, Food and Environment). In order to take into account these other aspects several indicators have been estimated including: population distribution and growth, household energy and water demands, irrigation energy demand for water movement and pumping, livestock land requirements and forage and water need, population food requirements as based on current food habits, food diet and optimal food calories requirements. In the optimization process several objectives can be optimized simultaneously; this is a key capability of the approach, but it should be also pointed out that the concurrent use of more objective can make more complex the interpretation of the results. An analysis has been implemented by focusing on 2 WEFE objecives at a time for optimization (maximization and/or minimization) while using other indicators as constraints. One with a focus on tradeoff analysis between food security and Bioenergy and another one focusing on the tradeoff between water demands and bioenergy. The optimizer show the results in the form of Pareto frontiers optimal solution. Each solution can be analyzed by final end users to analyze how much more energy is produced, the impact on the WEFE indicators and the spatial crop land allocation. Results point out that a wide range of “optimal” solution is produced. The analysis of outputs suggests: rice cultivation would need to be replaced in order to favor energy production (this is also because high quantities of rice are already produced in the region and so there is no need, under current scenario constraint, to produce more rice). For example by considering food calories indicator as more important, the most widely used crop used in the region would be cassava. It is also interesting to note, that even with very different crop land allocation and optimization the new optimal quantity of energy that can potentially be produced is similar and it is increased of about 25%, if compared with current management.

As already introduced briefly in the methodology and analysis of results it should be taken into account that the bioenergy potentials here estimated need to be considered as maximum attainable levels as based on biomass potential. In the reality several other factors would need to be considered such as: capital costs of plants, infrastructure issues related also to the capability to collect and store the residues for the year, skill level and labour availability and capacity. Also the variability of crop productivity may potentially impact the effectiveness of such plants and applicability in the long period. These and other factors will affect final bioenergy availability but are not addressed in this analysis. For example the estimated biogas potentials of crops are based on the technical potential of biomass, but actual potentials could be much lower in practice depending on conditions of the residues. Energy potential from animal manure, was not included as the availability of manure maybe limited because of i) the majority of animals are grown free during most of the time and therefore this limit the capacity to collect and recover the manure and ii) the soil fertility is already an issue in several regions; the manure component is therefore essential as nutrient source to restore and/or maintain the fertility and soil quality and could not be derived for energy supply.

This analysis is an example of how these strategies, combined with other key solutions for energy production (such as PV and Solar, etc.), can be effectively used to improve Senegal river basin to achieve an higher access to electricity level and an higher contribution of bio energy source. With about 7 million of people living in great part in rural areas, exploring such bio energy technology has showed its potential and also it showed the importance of applying WEFE Nexus concept in the assessment, thus allowing to identify higher productivity level but ensuring other important aspects.

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