Research Article

Modelling of Sudan's Energy Supply, Transformation, and Demand

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The study aimed to develop energy flow diagram (Sankey diagram) of Sudan for the base year 2014. The developed Sankey diagram is the first of its kind in Sudan. The available energy balance for the base year 2012 is a simple line draw and did not count the energy supply by private and mixed sectors such as sugar and oil industries and marine and civil aviation. The private and mixed sectors account for about 7% of the national grid electric power. Four energy modules are developed: resources, transformation, demand, and export and import modules. The data are obtained from relevant Sudanese ministries and directorates and Sudan Central Bank. “e!Sankey 4 pro” software is used to develop the Sankey diagram. The main primary types of energy in Sudan are oil, hydro, biomass, and renewable energy. Sudan has a surplus of gasoline, petroleum coke, and biomass and deficit in electric power, gasoil, jet oil, and LPG. The surplus of gasoline is exported; however, the petroleum coke is kept as reserve. The deficit is covered by import. The overall useful energy is 76% and the loss is 24%. The useful energy is distributed among residential (38%), transportation (33%), industry (12%), services (16%), and agriculture (1%) sectors.

1. Introduction

Figure 1 shows the energy Sankey diagram of USA as an example. The Sankey diagram is an important tool to visualize the energy balance for a system or a country or a region. The Sankey diagram depicts the energy flows from supply to demand taking into account transformation. Sankey diagram was developed over 100 years ago by the Irish engineer Riall Sankey to analyze the thermal efficiency of steam engines. Since then, it has been widely used. Besides visualization, Sankey diagram is a vital tool to identify sources of inefficiency and potential saving in the energy system.

For the preparation of Sankey diagram for a country, four modules are needed. The first is the demand module, which contains the details of the demand for end-use energy (both primary and secondary fuel) for the residential, services, industrial, agricultural, and transportation sectors [1]. The demand for each sector from primary and secondary energy is defined. For example, the demand of residential sector is electricity, oil products, and biomass for lighting, cooking, and HVAC. The second module is the transformation module. It consists of all energy transformation processes, such as

electricity generation, oil refining, and charcoal conversion. In these modules, the energy is divided into useful energy and lost energy. The useful energy is then distributed to demand sectors. The third module deals with the available resources. The main energy sources are coal, crude oil, natural gas, hydroelectricity, biomass, nuclear energy, and renewable energy such as solar, wind, and geothermal energy. The fourth module deals with energy import and export. There exist a number of models used to develop the energy supply and demand modules. Prominent energy models include MARKAL, LEAP, ENERGY 2020, MAPLE C, NEMS, and MAED. Details on these models and their implementation can be found in a number of published studies [2–4].

This study is aimed at providing Sankey diagram for Sudan for base year 2014. What is available now in Sudan is energy balance for 2012 [7] (cf. Table 1). However, the available energy balance data did count only the energy produced by public sectors. The energy produced by private and mixed sectors is not counted. These include the electric energy produced by oil refineries and sugar factories which constitute a significant share of Sudan energy mix. It also did not count for bagasse and bioethanol. Likewise, it does

FIGURE 1: Sankey diagram of USA. Source: [5]. Data is based on DOE/EIA-0035(2015-03), March 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal, and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End-use efficiency is estimated as 65% for the residential and commercial sectors, 80% for industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527.

TABLE 1: Sudan energy balance 2012 [6].

Demand sectors	Power		Oil		Biomass		Total	
	ktoe	%	ktoe	%	ktoe	%	ktoe	%
Residential	401	54.3	298	7.9	3088	62.2	3911	40.0
Transportation			2994	79.2			3073	31.4
Services	181	24.5	43	1.1	1303	26.2	1579	16.1
Industry	120	16.3	400	10.6	575	11.6	1133	11.6
Agriculture	36	4.9	43	1.1			85	0.9
Total	738	100	3778	100	4966	100	9781	100
Share of energy supply	7.5		38.6		50.8		100.0	

not count the petroleum associated gas (AG) and renewable energy, in particular photovoltaic energy. The most difficult part of this work is the data quality check. There exist a number of reports on Sudan's energy status. These reports include conflicting data, double counts, and inconsistent units. The authors have extensively verified the data from their original sources. Data on renewable energy status in Sudan is scarce as well. Extensive search including field survey was made to collect data on this area. Data on the demand side is not well documented as well and hence

enormous effort was exerted to collect the data from their original sources. The main contribution of this work is to make proper documentation of Sudan energy data on both supply and demand side. The other contribution is to produce Sudan's energy flow diagram for the first time.

2. Methodology

2.1. Data Collection. The energy supply, demand, and transformation data are obtained from the following reports:

FIGURE 2: Primary energy resources.

- (1) Annual report of Sudan Central Bank.
- (2) Annual reports from the Ministry of Oil and Gas [6, 7].
- (3) Annual report from the Directorate of Agriculture and Forestry [8].
- (4) Annual report from Sudanese thermal power generation corporation [9].

The collected data is further subjected to quality check for completeness, avoiding double counting and uncertainty assessment.

2.1.1. Completeness. The available reports on electric power generation in Sudan account only for power produced by the public sector. The power generation of private and mixed sectors is not counted by the published reports. For example, the power generation of petroleum refineries and sugar factory, as mixed sectors, is not accounted for in Sudan energy balance for 2012 [6]. This data gap is filled using field survey. There also exists no inventory of standby generators countrywide.

2.1.2. Avoiding Double Counting. Some data duplicate is found in the available literature. For example, ORC produced Naphtha which is used as feedstock to KRC to produce gasoline and other products; hence, it is double counted in Sudan energy balance for 2012 and the reports of Central Bank and the Ministry of Oil and Gas. The reports of ORC and KRC refineries are considered rather than Sudan Central Bank's reports.

2.1.3. Uncertainty Assessment. There is a lack of proper documentation of bagasse, animal waste, and agriculture waste. However, there are data of production of sugar, cereals, crops, cotton, and count of animals. The waste is estimated from production data. For example, bagasse is estimated from sugar production. The sugar recovery is taken as 9% of the crushed sugar cane and the bagasse is taken as 39.5% of the crushed sugar cane. The estimated bagasse is cross-checked by field survey of the sugar plants and it is found that the assumptions are accurate within 5% for all sugar factories. Similarly, the animal dung is estimated from animal count. The dung production is taken as 10.95, 1.83, 1.83, and 5.48 tons/animal/head for cows, sheep, goats, and camels, respectively [10]. The dung that is potential for energy use is taken as 10%. The agricultural waste is estimated using harvest index (HI) [11]. The harvest index for cereals, oil crops, and cotton is taken as 0.4, 0.52, and 0.16, respectively. The residue is calculated as amount of products multiplied by $[(1 - HI)/HI]$. The other challenge is that the portion of agriculture residue used as fuel is unknown as the residue is shared by many applications such as animal feed, building material, and pulp and paper industry. This is on the one hand. On the other hand, the residue is mostly left in the farm as a fertilizer or burned during land preparation. Under this circumstance, the ratio of agriculture waste accepted by Sudan energy balance 2012 was considered.

2.2. Energy Modelling. Although there exist a number of energy modelling software programs such Long Range Energy Alternative Planning Systems (LEAP), in this work, a simple Excel worksheet is used for energy modelling.

FIGURE 3: Energy demand by sector.

The energy framework for development of Sankey diagram consists of four modules [1].

- (1) Energy resource module: this module takes account of all the primary fuel such as petroleum, coal, natural gas, uranium, biomass, and renewable energy (cf. Figure 2).
- (2) Transformation module: the transformation module handles data on the conversion of primary fuel into secondary fuel such as power generation and conversion of crude oil in the refinery to secondary fuels.
- (3) Demand module: the demand module contains the details regarding the end-use energy demand for both primary and secondary fuel. The consumption sectors include agriculture, industry, services, residential, and transportation sectors (cf. Figure 3).
- (4) Import and export module: this module deals with energy import and export. The energy import and export are normally in the end-use form such as electricity and secondary fuel oil.

The data generated by the four modules for the base year 2014 is used to develop the energy Sankey diagram for Sudan. The software “e!Sankey 4 pro” was used. e!Sankey is widely used software for the development of Sankey diagrams for a country or a region.

3. Results and Discussion

The main sources of primary energy in Sudan are oil, hydroelectricity, biomass, and renewable energy. Coal, natural gas, and uranium are nonexistent in Sudan. The main transformation and conversion processes are electric power generation, oil refinery, and wood-to-charcoal conversion.

3.1. Electric Energy Supply and Demand

3.1.1. Hydroelectric Power. Table 2 shows the hydroelectric power generation plants in Sudan. The installed capacity, nominal capacity (MW), expected GWh, and year of establishment are given. The planned and under-construction hydroelectric power plants are also given. The total installed and potential hydroelectric power in Sudan is 4176 MW; the installed capacity is 1585 MW (38%).

3.1.2. Thermal Electric Power Generation. Table 3 shows the installed, under-construction, and planned thermal power plants. The installed power is 1400 MW and the under-construction and planned power are 405 MW and 600 MW, respectively. The installed thermal power generation is about 46% of the total installed public power generation (hydro + thermal). One important point in thermal generation is its diversity in prime movers and fuels sources. The prime movers in thermal generation include steam turbine (ST),

TABLE 2: Hydroelectric power plant (operational, under construction, and planned).

Number	Name	Year	Installed MW	Capacity Nominal MW	Production GWh
Operational plant					
1	Merowe Dam	2009	1250	1240	5580
2	Roseires Dam	1966	280	270	1050
5	Sennar Dam	1962	15	12	49
3	Jebel Aulia Dam	2003	30	19	55
4	Khasm El Girba Dam	1964	10	10	15
<i>Subtotal A</i>			<i>1585</i>	<i>1551</i>	<i>6749</i>
Under-construction plant					
5	Upper Atbra and Sitat	2015	323	320	834
6	Sennar upgrading	2015	11	13.7	66
Planned plant					
7	Shereik		420		2103
8	Kajbar		360		1799
9	Sabaloka		205		866
10	Dal Low		648		2185
11	Dagash		312		1349
12	Mograt		312		1214
<i>Subtotal B</i>			<i>2257</i>		<i>9515</i>
<i>Total (A + B)</i>			<i>384</i>		<i>16264</i>
Available power%			<i>38</i>		<i>39</i>

TABLE 3: Thermal power plant.

Number	Thermal power plant	Year	Prime mover	Fuel	Installed MW	Capacity Nominal MW	Available GWh
Operational thermal power plants							
1	Shahid Mahmoud Sharief 1 + 2 ST	1984	ST ¹	HCGO ²	60	28	212
2	Shahid Mahmoud Sharief 3 + 4 ST	1994	ST	HFO ³ + HCGO	120	110	840
3	Shahid Mahmoud Sharief 5 + 6 ST	2011	ST	HFO	200	190	1408
4	Shahid Mahmoud Sharief 1 + 2 GT	1992	GT ⁴	GO ⁵	50	34	265
5	Garri1: CCGT	2003	CCGT ⁶	GO + LPG	180	170	1346
6	Garri2: CCGT	2003	CCGT	GO + LPG	180	170	1346
7	Garri4: ST	2010	ST	Pet coke	110	100	675
8	Kusti	2013	ST	Crude oil	500	470	3590
9	Diesel generation		IC	Diesel			
<i>Available thermal power A</i>					<i>1400</i>	<i>1272</i>	<i>9682</i>
Under-construction and planned thermal power plant							
9	Al Fula	2016	ST	AG/NG ⁷	405	381	2908
10	Red Sea	2016	ST	Coal	600	534	4079
<i>Planned thermal power cycle B</i>					<i>1005</i>	<i>915</i>	<i>6987</i>
<i>Total (A + B)</i>					<i>2405</i>	<i>2187</i>	<i>16669</i>

¹ST: steam turbine.²HCGO: heavy coker gas oil (heavy gasoil).³HFO: heavy fuel oil (equivalent to number 6 fuel oil).⁴GT: gas turbine.⁵GO: gasoil.⁶CCGT: combined cycle gas turbine.⁷AG: petroleum associated gas; NA: natural gas.

TABLE 4: Electric power profile (GWh).

Year	Hydro	Steam turbine	Gas turbine	Diesel	Combined	Import	Production	Hydro%	Import%
2014	8914	1400	0	202	864	469	11848	75	4
2013	8317	1205	0	183	582	320	10607	78	3
2012	6619	1484	5	182	1145	74	9509	70	1
2011	6452	1631	1	161	210	0	8455	76	0
2010	6199	473	14	192	620	0	7499	83	0
2009	3236	887	94	309	1847	0	6372	51	0
2008	1466	1106	152	442	2340	0	5506	27	0
2007	1457	1057	371	140	1997	0	5021	29	0
2006	1368	1108	501	353	1192	0	4521	30	0
2005	1239	1047	319	385	1135	0	4125	30	0
2004	1107	1037	1256	349	0	0	3749	30	0
2003	1163	1168	210	328	0	0	3354	35	0
2002	1287	116	381	310	0	0	3094	42	0

TABLE 5: Oil industry thermal power generation plant.

Number	Oil industry power plant	Year	Prime mover	Fuel	kW
1	KRC (2 × 12 MW)	1999	ST	FG ⁹ + bunker	24000
2	KRC (2 × 12 MW)	2006	GT	FG + bunker	12000
3	ORC 50 Hz	1999	IC	Diesel	250
4	ORC 60 Hz ⁸	1999	IC	Diesel	500
5	Heglig oil field 1	na	IC	Diesel	25.5
6	Heglig oil field 2	na	IC	Diesel	11.5
7	Neem oil field	na	IC	Diesel	11.2
8	Canar oil field	na	IC	Diesel	0.8
9	Diffra oil field	na	IC	Diesel	3.9
10	Other (mainly the power for the oil pipeline)	na	IC	Diesel	1000
<i>Total</i>					37803

⁸FG: fuel gas mainly CH₄.

⁹Since 2014, it has become standby generator as the refinery is connected to national grid of 50 Hz.

gas turbine (GT), combined cycle of gas turbine (CCGT), and internal combustion (IC) engines. IC engines are used in remote areas that are not covered by the national grid. The fuels used include gasoil (GO), diesel (blend of gasoil and gasoline), heavy fuel oil (HFO) also called furnace and number 6 fuel oil, heavy coker gasoil (HCGO), crude oil, petroleum coke, and liquefied petroleum gas (LPG). Diversity is a merit; however, the use of gasoil in steam turbine is the weak point of thermal generation sector in Sudan. Gasoil is competitive oil as it is used by transportation and agriculture sectors, in addition to its high cost relative to heavy fuel oil and petroleum coke. But it seems that the use of gasoil in ST and GT generation is an issue of “energy security” rather than economic factors; otherwise, the use of gasoil is not a common practice in ST and GT power generation. Table 4 shows the electric power generation in Sudan in the period from 2002 to 2014. The hydroelectric power share increased from 42% in 2002 to more than 75% in 2014. This is mainly due to the inception of Merowe Dam in 2009. The imported electric power from Ethiopia increased to 469 GWh (4%) in 2014.

3.2. Private and Mixed Sectors Power Generation. There exist a number of private and mixed industries that produce their own power consumption. The major industries are as follows:

- (1) Oil refineries.
- (2) Oil fields production facilities.
- (3) Sugar industry.
- (4) Cement industry.
- (5) Sea port and civil aviation.
- (6) Others.

The power production by these sectors is not accounted for in Sudan energy balance 2012.

3.2.1. Oil Refinery. Table 5 shows the installed power of oil refinery and oil fields. The total installed power by oil industry is about 38 MW. A large portion of KRC refinery power generation is from waste heat and low grade fuel such as vent gas and oil slope (slurry). The electric power produced by oil

TABLE 6: Sugar industry power plant [12].

Number	Factory	Year	Sugar capacity		Bagasse ¹⁰		Power plant		
			Installed kton	Current kton	kton	ktoe	MW	D/Y	GWh
1	Kenana	1981	300	307.6	1350	580	20	210	326
2	Sennar	1976	70	73.1	321	138	6.5	210	33
3	Assalaya	1980	70	65.4	287	123	6.5	210	33
4	Guneid	1962	70	73.1	321	138	6.0	210	30
5	New Halfa	1966	70	59.5	261	112	6.0	210	30
6	White Nile ¹¹	2012	450	73.4	322	138	(104) 6.0 ¹²	210	33
<i>Total</i>			<i>980</i>	<i>652.1</i>	<i>2862</i>	<i>1230</i>	<i>(190) 96</i>		<i>485</i>

¹⁰Bagasse sugar ratio: 4.4.¹¹The design capacity of power plant is 104 MW.¹²Personnel contact.

TABLE 7: Solar radiation and sunshine duration in Sudan [13].

Station	Mean temperature	Sunshine duration	Solar radiation
	C	h	MJ/m ² /day
Port Sudan	28.4	9.0	20.87
Shambat	29.7	9.9	22.82
Wadi Medani	28.4	9.8	22.84
ElFashir	25.8	9.6	22.80
Abu Na'ama	28.8	8.8	21.90
Ghazala Gawazat	27.2	9.3	21.72
Dongala	27.2	10.5	24.06
Toker	28.8	7.3	17.60
Zalingi	24.5	8.8	22.98
Babanusa	28.2	8.9	21.30
Kadugli	27.5	8.5	21.30

industry is about 1% of the national grid electric power (the hydro and thermal power generation).

3.2.2. Sugar Industry. Sudan ranks high in sugar production among African countries. Sugar industry produces its own power consumption from bagasse, a byproduct of sugar cane. The installed sugar capacity is about 1.0 Mt of sugar/year. Table 6 shows the installed capacity of electric power plants in sugar factory. The installed capacity is about 190 MW, which is about 6% of the national grid electric power. However, the available capacity is 96 MW as the White Nile sugar factory is working at low capacity. Bagasse is sufficient to produce electric power for 210 days/year including cane crushing season of 180 days/year. Besides electric power, the factories also produce their own process heat for sugar cane mills, heating, and evaporation and crystallization process. The potential for high power generation in sugar plant is feasible. If cogeneration is installed, the process heat load will be reduced as the sugar mills and shredders will be electric driven rather than steam driven which in turn saves steam for power generation.

3.2.3. Standby Power Generation. All public utility services such as hospitals, universities, municipals, city water, and

commercial buildings have their own standby IC electric power generators. However, there is lack of inventory data on standby generators countrywide. In this work, a field survey was made and about 100 standby IC generators with name plate capacity of about 1.2 kW with diesel as fuel source have been established. However, due to lack of information on the operation hours of the standby power generation, it is excluded in the present study. Besides services, air aviation and sea port also rely heavily on off-grid generation.

3.2.4. Photovoltaic. Table 7 shows the solar radiation in a number of Sudanese cities. The average sunshine duration is about 9 h. Most of the solar installation in Sudan is photovoltaic cell. The total installed capacity is about 2 MW. About 50% of the installed capacity is by telecommunication industry. All remote off-grid antennas and satellites are solar driven.

3.2.5. Summary of Power Supply and Demand. Table 8 shows the power supply by various power producers and consumption by various sectors. The hydropower represents the biggest share of about 70% despite the fact that the installed capacity is about 54% of the total installed power capacity. This is due to the high outage associated with thermal power

TABLE 8: Electric power supply and consumption in base year 2014.

	Power supply (ktoe)					Power demand by sectors (ktoe)					Total
	Hydro	Thermal	IC	Import	PV ¹³	Residential	Industrial	Agriculture	Service	Trans.	
Public sector	767	677	17	40	0	534	151	52	283	0	1019
Oil industry		54		0	0	0	29	0	0	0	29
Sugar industry		61		0	0	0	61	0	0	0	61
Renewable		0		0	0.4	0	0	0	0.4	0	0
Total	767	285	17	40	0	534	240	52	283	0	1109
%	69.11	25.65	1.57	3.63	0.03	48.12	21.68	4.67	25.53	0.00	100.00

¹³PV: photovoltaic.

TABLE 9: Oil production.

Year	Oil production MMBPD	Export (000 tonnes) BPD
2014	42.4	11,093
2013	45.1	15,837
2012	37.4	7,210

TABLE 10: Sudan refineries.

Number	Refinery	Capacity (000 tonnes) BPD	
		Installed	Available
1	Khartoum Refinery Corporation (KRC)	100	100
2	Port Sudan Refinery Corporation (PRC)	21.7	0
3	Obeid Refinery Corporation (ORC)	15	15
4	Concorp Refinery	10	0
5	Abu Gabra Refinery	2	0
Total capacity		143.7	115

generation. The power demand by various sectors is also given. The residential sector has the biggest share of demand followed by the service sector.

3.3. Oil Supply and Demand. Table 9 shows Sudan's oil production in the last 3 years, after the separation of South Sudan. The portion of export is given as well. Besides oil production, a significant amount of associated gas (AG) is also produced. However, the AG is not utilized; it is flared. The historical and projected daily flared amount is about 15–17 MMSCFD from 2006 up to 2030 [14]. For this work, the minimum is considered (15 MMSCFD). Sudan has four oil refineries with a total installed capacity of 143.7 thousand BPD (cf. Tables 9 and 10). However, three of these refineries are out of service representing about 20% of the total installed refinery capacity.

Tables 11–17 show the fuel oil of ORC, KRC, import, total supply, total demand and supply and demand balance, and thermal power generation oil consumption, respectively. The main products include fuel oil, gasoil, kerosene, gasoline (Mogas), LPG, jet fuel, and petroleum coke. The surplus of benzene is for export. Sudan has surplus in some fuel oil

TABLE 11: ORC oil products (ton/year) [6].

Year	Fuel oil	Gasoil	Kerosene	Naphtha	Total ktoe
2010	361641.00	134446.00	38011.00	26981.00	405
2011	385330.00	141606.00	40405.00	27299.00	414
2012	385352.00	140899.00	41439.00	24245.00	148
2013	307604.00	114010.00	30937.00	19070.00	328
2014	339663.00	126600.00	32510.00	24547.36	312

and deficit in others. It has surplus in crude oil, gasoline, and pet coke. The surplus of crude and gasoline is for export while the surplus of pet coke is kept as reserve. The deficit of gasoil, LPG, and aviation is met from import. One of the causes of deficit in gasoil is its competitiveness. Gasoil is used by power generation, transportation, and agriculture sectors. As energy conservation measure fuel shift of gasoil is recommended for power generation and agriculture sector and gasoil is to be limited to transportation sector, heavy fuel oil is recommended for thermal power generation and total electrification of agricultural sector via using electric water pump for irrigation system rather than IC motors.

Table 17 shows summary of the oil supply and demand. The total supply is 7594 ktoe (7.594 Mtoe). This oil mix consists of crude oil, AG, and imported oil (gasoil, aviation, and LPG) as shown in Table 17. The imported oils represent about 19% of the total oil mix. 9.6% of the total supply is for thermal power generation including the electric power generated by KRC and ORC. The total energy mix is distributed as follows: 65.6% demand, 20.9% export, 12.9% energy conversion loss, and 1.32% flared gas. The demand is distributed to the following sectors: industry (11%), residential (8%), service (1%), transportation (79%), and agriculture (1%).

3.4. Biomass. The types of biomass used for energy in Sudan include

- (1) firewood,
- (2) charcoal,
- (3) agriculture residue,
- (4) bagasse,
- (5) bioethanol,
- (6) animal waste.

TABLE 12: KRC products (ton/year) [6].

Year	Crude	Fuel oil	Gasoil	Kerosene	Benzene	LPG	Jet fuel	HCGO	Pet coke	Total ktoe
2010	4265128	0	1860390	0	1241909	327413	133616	379768	322032	4379
2011	3854381	0	1651867	0	1150216	311840	133882	321413	285163	3964
2012	3738191	0	1655445	0	1099800	319690	117924	277230	268102	3850
2013	3403239	0	1515564	0	1009741	289363	79438	253612	255521	3501
2014	3405113	0	1379208	0	1067914	321453	107074	293368	236096	3573

TABLE 13: Fuel import (ton/year) [6].

Year	Gasoil	LPG Ton	Aviation	Total ktoe
2010	337864	37760	136538	540
2011	653661	92282	150459	945
2012	628063	114013	109110	899
2013	898842	195335	82674	1244
2014	1159119	132903	66593	1427

3.4.1. Bagasse and Ethanol. Table 18 shows the sugar produced by 6 Sudanese sugar factories. Bagasse is estimated from the produced sugar. It is taken as 39.5% of crushed sugar cane and the sugar recovery is taken as 9% of the sugar cane. Hence, the bagasse sugar ratio is 4.4-ton bagasse/ton sugar. Table 18 also shows the bioethanol production. Bioethanol is produced from molasses. All bioethanol produced is from Kenana sugar company. It should be remembered that all bioethanol is for export.

3.4.2. Firewood and Charcoal. Tables 19 and 20 show the firewood and charcoal, respectively, obtained from the annual report of the Directorate of Agriculture and Forestry of Sudan. It is clear that there is large data missing/gap. When these data are compared with data in the open literature, a large variation is found. Hence, these data are not considered and literature data is rather considered.

Table 21 shows firewood and charcoal production obtained from the open literature for some years as a cross-check. The data of Sudan energy balance of 2012 is adopted in this work as it is close to that given by other references.

3.4.3. Agriculture Residues. Table 22 shows the cereals, oil crops, and cotton production. The agricultural waste is estimated using harvest index (HI). The harvest index for cereals, oil crops, and cotton is taken as 0.4, 0.52, and 0.16, respectively. The agriculture waste is calculated as the amount of crop multiplied by $[(1 - \text{HI})/\text{HI}]$ [11]. The portion of agriculture residue used as fuel is very small as the majority is used as animal feed and building material and in pulp and paper industry, among others. On the other hand, the agriculture waste is mostly burned during land preparation for the next season. The data is cross-checked against Sudan energy balance of 2012 and is found to be consistent.

3.4.4. Animal Waste. Sudan is rich with cows, sheep, goats, and camels, besides donkeys, horses, and chickens. Table 23 shows the animal counts. The animal dung is estimated from average dung production per head. The dung is generally used for biogas production. The dung available for biogas production is estimated by many researchers as 10% [16]. Currently, there are no reports for biogas production in Sudan. There is some biogas production in the 1980s; however, with the inception of crude oil production, biogas production was abandoned nationwide. Hence, the animal waste is not considered in the energy balance for the base year 2014 as there was no information or rates of use in the energy sector. Table 24 shows summary of biomass supply and demand.

3.5. Sankey Diagram. Sudan Sankey diagram has been developed using the energy supply, transformation, and demand data obtained for the base year 2014 (cf. Figure 4). The Sankey diagram gives a detailed flow pattern indicating the proportional consumption of primary and secondary energy in different energy demand sectors. It also shows the energy loss during transformation and conversion. The main features of the Sankey diagram are as follows:

- (1) Primary energy: Sudan's primary energy consists of oil (39%), biomass (56%), hydroelectricity (5%), and a very small portion of solar energy (photovoltaic). Besides primary energy, Sudan imports 1427 ktoe of fuel oils (gasoil + aviation + LPG) and 40 ktoe of electricity from the neighbouring country of Ethiopia. The import is about 7% of Sudan's energy mix. However, natural gas, coal, nuclear energy, and other renewable energy sources are nonexistent in the country's primary energy mix, despite the huge potential of solar, wind, and geothermal energy. The high proportion of biomass is due to the large population located in rural areas (70% rural population). They have no access to national grid electricity, fuel gas, and kerosene and therefore are absolutely biomass dependent in meeting their demand for cooking, heating, and lighting.
- (2) Transformation and conversion: the transformation processes in Sudan's energy balance are power generation (hydro, oil, and bagasse), refinery of crude oil to secondary fuels, and conversion of wood to charcoal. The transformation and conversion and other losses are about 25% of the end-use energy. These losses are thermodynamic loss and energy management

TABLE 14: Sudan fuel demand/consumption (ton) [6].

Year	Fuel oil	Gasoil	Kerosene	Benzene	LPG	AV	Pet coke	Diesel	Total
2010	555290	2380175	3018	824232	398347	235344	340858	26131	4763395
2011	531991	2358366	3497	838924	231382	289474	211637	22384	4487655
2012	348063	2544450	3119	901671	374968	223797	265292	19887	4681247
2013	337800	2475863	4270	918269	357588	190060	189236	31088	4504174
2014	290696	2616231	3744	895420	397251	144718	245672	27913	4621645

Energy balance, Sudan 2014

Unit: ktoe

FIGURE 4: Sankey diagram for Sudan. The data used is energy data for the year 2014. The data does not include private power generation. The renewable energy includes only solar photo voltaic power; the other types of energy, such as wind and geothermal, are not included. The hydro power and biomass energy are made as main categories in energy balance. The power generation efficiency and fuel conversion loss and emissions in the refinery are considered. All units are in ktoe (ton of oil equivalent).

loss. It is worth highlighting two examples of energy management loss:

(a) Lack of cogeneration in sugar industry: the potential electric power generation in sugar

industry is double the present level if cogeneration in the sugar industry is introduced [12]. Cogeneration is the standard practice in sugar industry worldwide. Lack of cogeneration made the sugar industry in Sudan burn bagasse

TABLE 15: Supply and demand balance (000 tonnes) [6].

Year	Fuel oil	Gasoil	Kerosene	Benzene	LPG	Naphtha	AV	H. coker GO	Pet coke	Diesel
2010	-295	-79	22	418	-33	20	35	380	-19	-26
2011	-257	47	20	311	173	20	-5	321	74	-22
2012	-248	-227	5	231	59	8	3	277	3	-20
2013	-124	15	15	91	127	18	-28	254	66	-31
2014	-75	64	13	154	50	17	24	292	15	-28

TABLE 16: Fuel demand for thermal electric power base year 2014 [9].

Fuel	Fuel oil	Benzene	H. coker GO	Pet coke	Diesel	Total
tonne	222844	240981	162581	14899	33916	425
ktoe	214	258	156	11	38	677

TABLE 17: Oil supply and demand in 2014.

Item	ktoe	%	Share%
Crude oil production	6067	79.89	
Associated gas	100	1.32	
Gasoil	1206	15.88	
Aviation	71	0.93	
LPG	150	1.98	
Subtotal A	7594	100.00	
Flared AG	100	5.93	1.32
Crude export	1587	94.07	20.90
Subtotal B: export + loss	1687		
Subtotal C = A - B	5907		
Refinery conversion + distribution + emission	30	3.19	
Benzene export	165	17.82	
Power production	677	73.13	
KRC + ORC (internal consumption for power generation)	54	5.85	
Subtotal D = C - oil used in power generation	926	100.00	12.19
Residential	398	8.00	
Transportation	3935	79.00	
¹ Service	50	1.00	
Industry	548	11.00	
Agric.	50	1.00	
Fuel for consumption by sectors	4981		65.59
Total by sectors	5907	100.00	100.00

¹Service includes public buildings, school, universities, hospitals, municipals, and so forth.

inefficiently; otherwise bagasse poses serious hazard to factory safety.

- (b) Flaring of AG: about 15 MMSCFD or 100 ktoe (1.7% of the oil supply) is attributed to flaring of AG. In the oil fields, a significant amount of AG is produced. AG produced is, however, not utilized; it is rather flared. The study conducted by [14] indicated that AG is useful primary energy and if utilized in power generation it can drive steam turbine power plant of 80 MW or can be utilized to produce LPG of annual value of \$40 M/year.

- (3) Demand: 74% of the total energy demand is useful energy and 26% is loss. 49% of the total loss is due to

low efficiency of conversion from wood to charcoal (charcoal conversion efficiency is 33%). The useful energy is distributed among the various demand sectors: agriculture (1%), service (16%), industry (12%), residential (39%), and transportation (32%) sectors.

The developed Sankey diagram is the first of its type in Sudan. The main differences between the present and previous energy balance are the following:

- (1) The previous energy balance is presented in simple line draw diagram rather than a professional Sankey diagram as all lines representing different flows are of the same size.

TABLE 18: Bagasse and bioethanol production [15].

Year	Kenana	New Halfa	Capacity (000 tonnes/year)				Total	Bagasse		Bioethanol ¹⁴ (000 m ³)
			Gunied	Sennar	Assalya	W Nile		Mton	ktoe	
2002	376	85	94	78	64		697	3059	1315	
2003	398	83	87	85	76		729	3200	1376	
2004	428	88	87	79	74		755	3314	1425	
2005	393	73	87	72	88		713	3127	1344	
2006	400	85	81	81	81		728	3195	1373	
2007	405	83	87	93	90		758	3326	1430	
2008	402	81	85	86	91		745	3268	1405	
2009	382	84	88	87	98		739	3241	1393	
2010	276	57	88	77	75		574	2518	1082	
2011	356	75	98	71	94		693	3040	1307	40
2012	350	66	92	77	90	6	680	2985	1283	55
2013	471	56	77	76	90	73	843	3698	1590	67
2014	308	60	73	73	65	73	652	2862	1230	70

¹⁴ All bioethanol is produced from Kenana sugar factory.

TABLE 19: Firewood by state in m³ [8].

Year	North	Khartoum	Central	Eastern	Kordofan	Darfur	Total
2005	4267	0	52087	31228	129324	10311	227217
2006	3547	0	37632	16038	577803	138903	773922
2007	5379	0	70113	71116	23792	29079	199479
2008	5153	770	83808	33734	278401	64868	466733
2009	3000	0	39828	15360	0	0	58188
2010	11855	0	75621	29140	127089	33056	276761
2011	6538	340	72992	34307	99828	45955	259960
2012	3410	500	49490	9753	9311	0	72464
2013	3150	0	52079	8400	6515	0	70144
2014	200	0	23757	9627	13837	52363	99784

TABLE 20: Charcoal by state (tons) [8].

Year	North	Khartoum	Central	Eastern	Kordofan	Darfur	Total
2005	895	0	29788	15615	5254	720	52272
2006	912	0	10479	855	13201	2219	27665
2007	1568	0	17239	507	0	1676	20990
2008	1012	158	16016	42479	11820	1015	72501
2009	0	0	310	2995	0	0	3305
2010	8556	0	10004	30545	557026	1512	607643
2011	19276	0	192198	39941	24109	70082	345606
2012	0	0	3200	9875	0	0	13075
2013	0	0	3500	5930	0	0	9430
2014	0	0	1302	155	0	0	1457

TABLE 21: Estimate firewood and charcoal.

Source	Firewood ktoe	Charcoal ktoe	Total as firewood ktoe
[7]	3146	878 (2926) ¹⁵	6072
[16]	2410	795 (2650)	5060
[17] ¹⁶	3944	1328 (4427)	8371

¹⁵ Data in brackets is firewood converted into charcoal with conversion efficiency of 33%.

¹⁶ The original data is given as consumption per capita.

TABLE 22: Agriculture waste.

Year	Sorghum	Millet	Wheat	Groundnut HI [11] kton/year	Sesame	Sun flower	Cotton	Total residue	
	0.4	0.4	0.4	0.52	0.52	0.52	0.16	Mton	ktoe
2002	4.394	578	247	990	274	4	72	2.79	2105
2003	2.825	581	330	550	122	18	86	2.46	1852
2004	4.69	769	398	790	399	7	66	3.21	2418
2005	266	280	364	520	277	12	86	2.56	1932
2006	4327	675	416	555	400	44	75	9.44	7117
2007	4.999	796	669	564	242	73	61	3.34	2516
2008	3.869	721	587	716	350	100	24	3.17	2389
2009	4.197	637	641	942	318	247	31	3.48	2620
2010	2.63	471	403	549	248	46	12	2.16	1624
2011	4.605	634	292	1.185	363	124	14	1.92	1445
2012	1.883	378	324	1.032	187	92	55	1.60	1208
2013	4.524	1.09	265	1.767	562	86	25	1.14	857
2014	2.249	359	193	963	205	56	31	2.12	1600

TABLE 23: Animal waste.

Year	Cows	Sheep Dung production (tons/year/head) [10] Million head	Goats 1.83	Camels 5.48	Dung	
	10.95	1.83	1.83	5.48	Mton	ktoe
2002	39.479	48.136	41.485	3.343	61	25690
2003	39.667	48.44	42.03	3.503	62	25878
2004	39.76	48.91	42.179	3.519	62	25971
2005	40.468	49.797	42.526	3.908	63	26479
2006	40.994	50.39	42.756	4.078	64	26821
2007	41.138	50.651	42.938	4.238	64	26958
2008	41.426	51.067	43.104	4.46	65	27185
2009	41.563	51.555	43.27	4.56	65	27321
2010	41.761	52.079	43.441	4.623	66	27479
2011	29.618	39.296	30.649	4.715	48	19986
2012	29.84	39.483	30.837	4.751	48	20124
2013	30.01	39.568	30.984	4.773	48	20225
2014	30.191	39.846	31.029	4.792	49	20337

- (2) The energy balance accounts only for power produced by public sectors. For example, the electric power produced by the refinery and sugar factory is not accounted for in the overall balance. Likewise, renewable energy though small is not accounted for as well.

4. Conclusion

The study provides important information on Sudan's energy sector covering supply and demand sides as well as conversion, distribution, and transmission. For the supply detailed data on electric power generation, oil production and conversion, biomass sources and conversion, and renewable energy

was given. Energy import and export were also reported. On the demand side, detailed data of different sectors is reported. The work provided energy flow diagram (Sankey diagram) for the first time. Sankey diagram is an important piece of information for decision-makers. It can be used to develop strategies and identify potential saving, opportunities, and mitigation measures. The weak point of Sudan's energy status is solar energy despite the high intensity of solar radiation and long sunshine hours across the country.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

TABLE 24: Biomass supply and demand.

Supply	ktoe	%	Demand	ktoe	%
Firewood	3146	28.68	Residential	3553	32.39
Charcoal	2925 (965) ¹⁷	26.66	Services	1496	13.64
Agricultural residue	1600	14.58	Industry	662	6.03
Bagasse	1230	11.21	Transport	0	0.00
Bioethanol	36	0.33	Agriculture	0	0.00
Animal waste	2034 ¹⁸	18.54	Electric power	1230	11.21
			Charcoal conversion loss	1960	17.87
			Export ¹⁹	36	0.33
			Not utilized ²⁰	2034	18.54
Total	10971	100		10971	100.00

¹⁷ Data in brackets is firewood converted into charcoal with conversion efficiency of 33%.

¹⁸ Animal waste is not considered as there is no record for animal waste utilization in the base year 2014.

¹⁹ All bioethanol is exported.

²⁰ Animal waste is not utilized.

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