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ORIGINAL RESEARCH

Sustainable and renewable implementation multi-criteria energy model (SRIME)—case study: Sri Lanka

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Abstract Sustainable and renewable are certainly very appreciated terms nowadays. These words may summarize a whole new attitude towards our world and the people who live in it. This paper's goal is to define an original multi-criteria energy model, named SRIME, specially designed for developing countries. First, an extensive research will be carried out on: energy demand; potential renewable energy, its current know-how and potential future development; potential avoided emissions (CO_2, NO_X, SO_2); and the possible international support versus the in-country possibilities. The precedence constraints will be applied to establish in which degree renewable energy may be substituting for the fossil fuel: the purely economic approach will give way to a sustainable, renewable, development focused energy planning. It must be noted that an innovative function has been specifically included in the SRIME, which evaluates, applying the precedence constraints, the influence renewable energy may have on developing countries rural health and education. Six functions have been established: replaceable amount of fossil energy; CO_2, NO_X and SO_2 avoidable emissions; rural health and education development maximization; and the cost function. These functions will be optimized through the Chebyshev distance (L_∞) compromise programming minimization, so that the Pareto optimal solution may be obtained.

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Keywords Renewable and sustainable energy planning · Developing countries · Multi-criteria decision making · Avoided emissions · Global warming

Abbreviations

AC	Alternating current
BT	Biomass thermal
BEG	Biomass electricity generation
GDP	Gross domestic product
GOSL	Government of Sri Lanka
HH	Household
HMDP	High materially developed countries
IAEA	International Atomic Energy Agency
LEC	Levelized energy cost
L_k	k-dimensional distance
LMDC	Low materially developed countries
LPC	Linear programming computation
LRY	Real GDP per capita
MCDM	Multi-criteria decision making
MDG	Millennium development goals
MMTCDE	Million metric tons of carbon dioxide equivalents
MSW	Municipal solid waste
NCRE	Non-conventional renewable energy
PH	Pico hydro
PUCSL	Public Utilities Commission of Sri Lanka
PV	Photovoltaic system
RE	Renewable energy
SH	Small hydro
SHS	Solar home systems
SL	Sri Lanka
SLSEA	Sri Lanka Sustainable Energy Authority
SRIME	Sustainable and renewable implementation multi-criteria energy
UN	United Nations

WP	Wind power
WPP	Wind power plant

Introduction

The MCDM has been used over the years [1, 2], and is indeed a currently widely used tool for energy applications [3–6]. The aim of this paper is to focus on a set of sustainable and renewable factors that will be assessed through a precedence constraints evaluation. The optimal solution will be then chosen among the possible solutions for every one of the six equations, applying the Linear Programming Computation (LPC). The best compromised solution is then found among the Pareto optimal solutions [7], which will allow rejection of the solutions corresponding to any of the six optimizing equations that are found to be situated furthest from the rest of the optimal values obtained for the remaining equations. This way the dominating solutions will be softened, letting energy planners base their decisions on a solution that can not be improved without making at least one of the variables worse off.

This method's greatest challenge is how investigators and then planners will decide to calculate the weights to be applied to every one of the six equations. This decision will require a broad consensus among a wide range of experts so that decisions are not postponed, generating conflict, wasting time and, therefore, damaging future programming.

The subjective part of the compromise programming is also a demanding issue, which has to be carefully and professionally performed. The value given to the different subjects must be thoroughly assessed, avoiding a personal opinionated view from the experts.

SRIME model

Figure 1 shows the steps that are proposed in this model, which has been specifically designed for low materially developed countries. The first stage is to carry out a thorough evaluation of the current energy demand, and subsequent future needs. Secondly, the possible renewable solutions will be assessed, taking into account the in-country possibilities, along with the international support, aiming to enunciate the first function, using the precedence constraints.[1] The third step will be to study the potentially avoidable emissions so that the corresponding three functions may be stated (F_2, F_3, F_4). Then the fifth function will come from a deep study of the possible interactions between health and education and renewable energy, according to the parameters described by the UN and other international organizations. The last phase is to enunciate the cost function (F_6).

The L_k distances will then be minimized, according to the chosen weights, so that a compromised solution may be selected among the several obtained by the preferred optimization tool.[2]

Functions

Maximization of RE potential capacity: F_1

The so-called green economy focuses on the various advantages our world shall enjoy if we were to go green [8–11]. Not only climate change is involved here but also the potential enhancement of the overall development factors, especially the health co-benefits. You may find the corresponding equation and Table 1 below, which includes a summary of the potential precedence constraints the authors have chosen to be applied [12–14].[3]

$$F_1\left(x_{11}, x_{12}, \ldots, x_{ij}, \ldots, x_{\mathrm{nm}}\right) = A_{11}x_{11} + A_{12}x_{12} + \cdots + A_{\mathrm{nm}}x_{\mathrm{nm}} \quad (1)$$

Environmental impact minimization: F_2, F_3, F_4

Environmental impact has ben a major concern in the world for the past ten years. Local researchers are indeed looking into potential present and future sustainable possibilities [15, 16].

These are the three corresponding functions:

$$F_2\left(x_{11}, x_{12}, \ldots, x_{ij}, \ldots, x_{\mathrm{nm}}\right) = B_{11}x_{11} + B_{12}x_{12} + \cdots + B_{\mathrm{nm}}x_{\mathrm{nm}} \quad (2)$$

$$F_3\left(x_{11}, x_{12}, \ldots, x_{ij}, \ldots, x_{\mathrm{nm}}\right) = C_{11}x_{11} + C_{12}x_{12} + \cdots + C_{\mathrm{nm}}x_{\mathrm{nm}} \quad (3)$$

$$F_4\left(x_{11}, x_{12}, \ldots, x_{ij}, \ldots, x_{\mathrm{nm}}\right) = D_{11}x_{11} + D_{12}x_{12} + \cdots + D_{\mathrm{nm}}x_{\mathrm{nm}} \quad (4)$$

$B_{ij}/C_{ij}/D_{ij}$: life cycle $CO_2/NO_x/SO_2$ avoided emissions (ton/energy unit)

For all $B_{ij} \geq 0$; $C_{ij} \geq 0$; $D_{ij} \geq 0 \Rightarrow$ max F_2; F_3; F_4 - optimal avoided emissions maximization

[1] The authors are aware of the fact that there are many other optimization methods, like the cascade optimization or the ideal point discriminant analysis [1], and have indeed checked the obtained results using some of the mentioned methods, obtaining similar results.

[2] Please note subscript i denotes every RE type, and j denotes the different sectors; i.e., x_{ij} denotes the amount of fossil fuel (ktoe) replaced by RE i in sector j.

[3] Coefficients A are non-dimensional and obtained through precedence constraints, where no energy or cost quantification is involved. These precedence constraints are based on the factors showed below in Table 1.

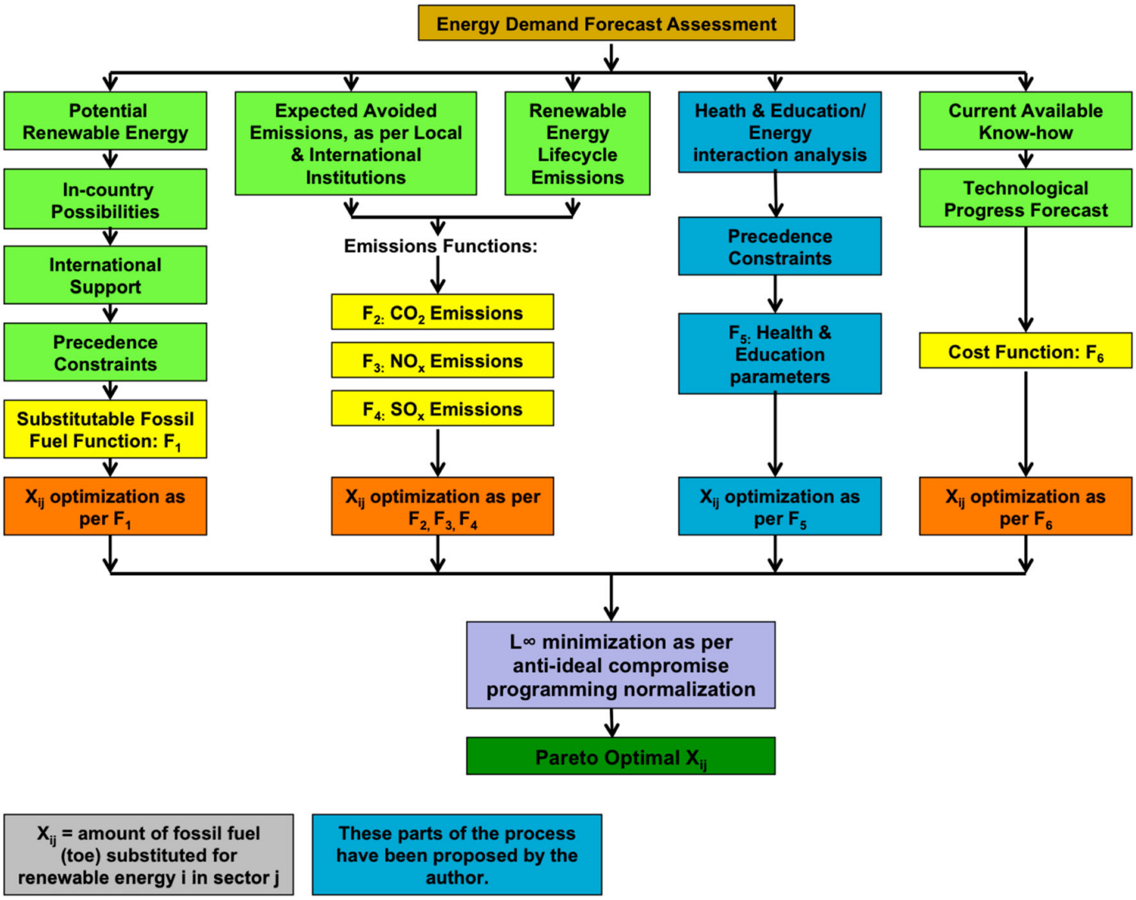

Fig. 1 SRIME energy model. Own construction

Table 1 Precedence constraints

Technological factors	Application	Energy planning	Fossil fuel environmental impact
Technological demand	Operating time	Political interest	Fossil fuel environmental impact
Potential investigation	Implementation issues	Current price compared with conventional energies	
Know-how up-to-date	Integration possibility	Social demand	
Technology improvement (possibly locally manufactured equipment)	Potential demand	Legislative forecast	
Current technological level to apply the alternative energy	Supply availability		

Own construction

Coefficients B_{ij}, C_{ij}, D_{ij} are obtained from official statistics and specialized publications.

Maximization of the most rural development friendly types of RE, aiming to improve health and education

One of the most usual indicators to estimate energy demand is the GDP growth rate. LEC and LRY commonly enjoy a high degree of causality. However, while HMDP show a bidirectional causality, LMDP only dictate a uni-directional causality from LRY to LEC [17]. As you can see below in Fig. 2, this is confirmed by the SL official data.

This is the corresponding equation:

$$F_5(x_{11}, x_{12}, \ldots, x_{ij}, \ldots, x_{nm}) = E_{11}x_{11} + E_{12}x_{12} + \ldots + E_{nm}x_{nm} \quad (5)$$

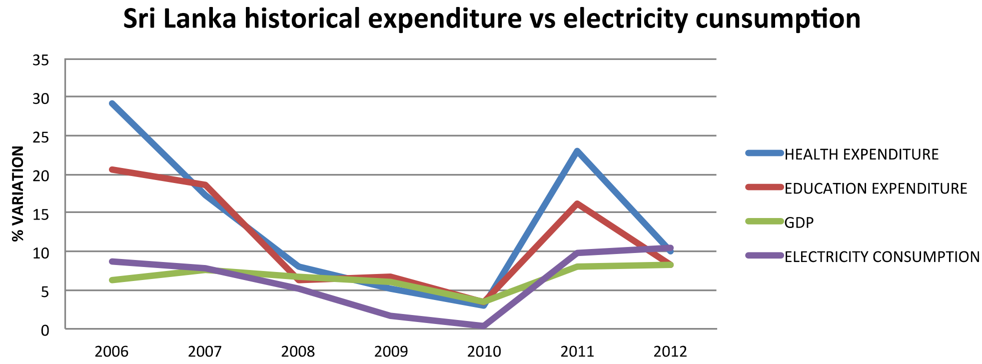

Fig. 2 SL expenditure vs energy consumption. Prepared by the authors based on official data [18–23]

Coefficients E_{ij} are non-dimensional and obtained through precedence constraints, where no energy or cost quantification is involved. These precedence constraints are based on:

1. Identified health and education ad-hoc applications.
2. Low overnight capital cost/unnecessary donor support for health and education enhancing applications.
3. Low maintenance cost.
4. Unnecessary maintenance contract.
5. Long lasting systems for health and education purposes.
6. Short distance from health and education centres to energy source.
7. Safe from being stolen in rural environment.
8. Low rural environmental impact.
9. Predictability.
10. Batteries not required for health and education purposes.
11. Alternating current.
12. Possible modularity/size accommodation for schools and hospitals.
13. Added benefits for rural development.
14. In-country development: manufacturing, training, etc.
15. Low LEC.
16. Hospitals and schools space efficiency for rural development.
17. Low or inexistent waste generation.

Cost minimization of substitution of renewable for existing conventional energy: F_6

$$F_6(x_{11}, x_{12}, \ldots, x_{ij}, \ldots, x_{nm}) = G_{11}x_{11} + G_{12}x_{12} + \cdots + G_{nm}x_{nm}$$

$G_{ij} =$ initial investment or production cost/energy unit

$$G_{ij} \geq 0 \text{ or } 0 \leq G_{ij}. \tag{6}$$

This function can also consider the renewable energy subsidies, therefore affecting the C coefficients. Another possibility can be to modify the coefficients, aiming to reach the best possible subsidy for every RE.

As per coefficients B_{ij}, C_{ij} and D_{ij}, coefficients G_{ij} are also obtained from official sources.

Restrictions

The restrictions to be applied are described below in Table 2, having in mind the following [1, 3, 12 and own construction]:

S_j: Energy demand of application j, calculated as: $S_j = p_j - i_j$; where p_j is the energy demand corresponding to sector j and i_j is the amount of fossil fuel renewable sources can not replace.

S_e: Energy demand of application i, calculated as: $S_e = p_e - i_e$; where p_e is the energy demand corresponding to sector e and $i_{e.}$ is the amount of fossil fuel renewable sources can not replace.

P_i: Potential application of renewable source i in the corresponding sector.

R_i: Minimum amount of conventional energy renewable sources can replace, as RE has already replaced this amount.

Compromise programming

As indicated by Linares et al. [24–26], to obtain the set of compromised solutions, both the normalized Manhattan distance, L_1 or the Chebyshev distance, L_∞, may be

Table 2 Restrictions

Non-electric energy use	Electric energy use	RE potential production	Current RE systems[a]
$\sum_{j=1}^{n} X_{ij} \leq S_j$ (7)	$\sum_{i=1}^{l} X_{ie} \leq S_e$ (8)	$X_{ie} + \sum_{j=1}^{m} X_{ij} \leq P_i$ (9)	$X_{ie} + \sum_{j=1}^{m} X_{ij} \leq R_i$ (10)

Own construction

[a] This restriction may also establish certain priorities in terms of advising the type of plant to be planned, always respecting the previous restrictions

Table 3 Normalized distances to be minimized

L_1	L_k	L_∞
$L_1 = \sum_{i=1}^{3} W_i \frac{F_i^* + -F_i(x)}{F_i^* + -F*i}$ (12)	$L_k = \lambda\left[\frac{W_1 f_1(x)}{F_1^* + -F*1} + \frac{W_2 f_2(x)}{F_2^* + -F*2} + \frac{W_3 f_3(x)}{F_3^* + -F*3}\right] + (1-\lambda)D\ 0 \le \lambda \le 1$ (13)	Min $L_\infty = D$ (14)

Own construction

minimized [27, 28]. Nonetheless, L_k will also help us obtain the optimal solution. Equation (11) below shows the general definition for L_d. Equations (12), (13) and (14) show the normalization to be carried out and Table 3 the distances that must be minimized.

$$d = \left[\sum_{j=1}^{n} |x1j - x2j|^d\right]^{1/d} \quad (11)$$

Taking into account that W_i is the weight or preference assigned by the decision makers, the distances to be minimized may be found below in Table 4.

Case study: Sri Lanka

The authors have prepared a sectorial energy consumption forecast for 2015 (see Table 5; Fig. 3) and the estimated generation and capacity mix (see Figs. 4, 5). The global electricity data has been obtained from the Long Term Generation Expansion Plan 2013–2032, prepared by the Ceylon Electricity Board, and the rest of he energy consumption and the electricity sectorial data has been estimated by the authors based, on official and private documentation [29–50].

The optimization equations

F_1. Maximization of RE potential capacity

SL is very much dependent on petroleum, which currently accounts for approximately 24 % of SL import bill and 45 % of exports. The demand has been doubled, in value terms, during the last 3 years [52]. The geo-climatic settings are particularly conducive, though, to harnessing hydro resources. The climate is largely determined by the meteorological conditions caused in the Indian sub continent due to the tropical circulation [53]. The current hydro power stations are operated to meet both peak and base electricity generation requirements. A 400 MW potential has been identified for small hydropower projects [54], typically characterised with less than 10 MW capacities [53]. 128 projects, totalling 271 MW, have been already commissioned as of 31/12/2014 [55]. Once these projects are available for power generation, will be carefully followed-up by PUCSL [56]. In terms of wind power, GOSL would like to go from the current 5 % to reach 10 % by 2017 and 14.1 % by 2022 [56]. There are close to 500 km^2 of windy areas with good-to-excellent wind resource potential. However, only a portion of this is deemed feasible to be harnessed because of technical and system limitations [57]. As of 31/12/2013, there are 10 commissioned projects, which will add 78.45 MW capacity to the grid [55] and also some possible future WPPs [58–61]. The wind potential has been estimated as 20,000 MW. In terms of biomass, Gliricidia sepium has been recently appointed as the fourth plantation crop after tea, rubber and coconut. Biomass application in electricity generation is not yet

Table 4 Restrictions summary

Distance	$d = 1$: Manhattan distance, L_1	$d = 2$: Euclidean distance, L_2	$d = \infty$: Chebyshev distance, L_∞
Restrictions	$\sum_{j=1}^{n} X_{ij} \le S_j$ (15)	$\sum_{j=1}^{n} X_{ij} \le S_j$ (15)	$\sum_{j=1}^{n} X_{ij} \le S_j$ (15)
	$\sum_{i=1}^{l} X_{ie} \le S_e$ (16)	$\sum_{i=1}^{l} X_{ie} \le S_e$ (16)	$\sum_{i=1}^{l} X_{ie} \le S_e$ (16)
	$X_{ie} + \sum_{j=1}^{m} X_{ij} \le P_i$ (17)	$X_{ie} + \sum_{j=1}^{m} X_{ij} \le P_i$ (17)	$X_{ie} + \sum_{j=1}^{m} X_{ij} \le P_i$ (17)
	$X_{ie} + \sum_{j=1}^{m} X_{ij} \le R_i$ (18)	$X_{ie} + \sum_{j=1}^{m} X_{ij} \le R_i$ (18)	$X_{ie} + \sum_{j=1}^{m} X_{ij} \le R_i$ (18)
		$W_1 \frac{F_1^* + -F_1(x)}{F_1^* + -F*1} \le D$ (19)	$W_1 \frac{F_1^* + -F_1(x)}{F_1^* + -F*1} \le D$ (19)
		$W_2 \frac{F_2^* + -F_2(x)}{F_2^* + -F*2} \le D$ (20)	$W_2 \frac{F_2^* + -F_2(x)}{F_2^* + -F*2} \le D$ (20)
		$W_3 \frac{F_3^* + -F_3(x)}{F_3^* + -F*3} \le D$ (21)	$W_3 \frac{F_3^* + -F_3(x)}{F_3^* + -F*3} \le D$ (21)

Source: own construction

Table 5 2015 SL sectorial energy consumption forecast (ktoe) [29–50]

	Electricity	LPG	Gasoline	Naphta	Avgas	Kerosene	Avtur	Diesel	Foil	Coal	Bagasse	Fwood
Agriculture								3.1	8.6			
Industries	372.4	36				25.1		85.6	180.7	83	65.1	1961
Transport		1.8	981.8	2.7	0.2		486.5	1924	2.7			
Education	3.9											
Religious	6.7											
HH	428.6	105.4				143.1						3739.2
Hotels	20.9	1.9							8.3			
Street light	14.6											
Health	15.7	1.2							2.4			
Commercial	236.1	137.1				15.3		14.7	13.8			427.8

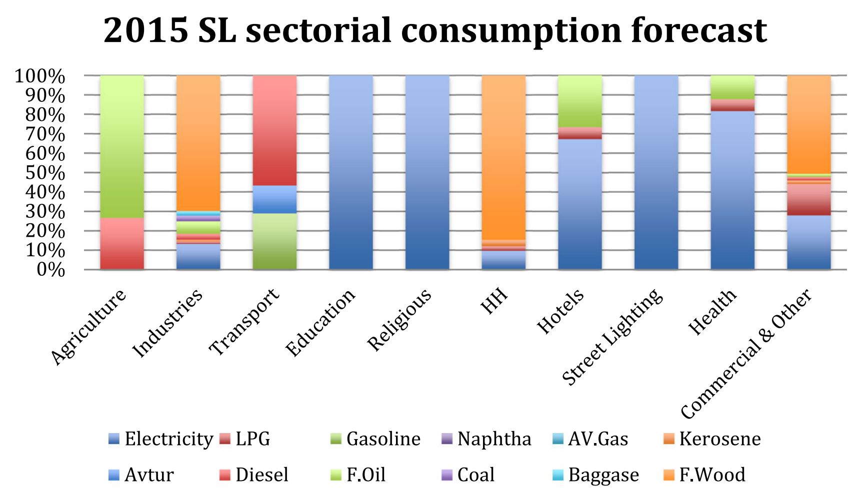

Fig. 3 2015 Sri Lanka sectorial energy consumption forecast [29–50]

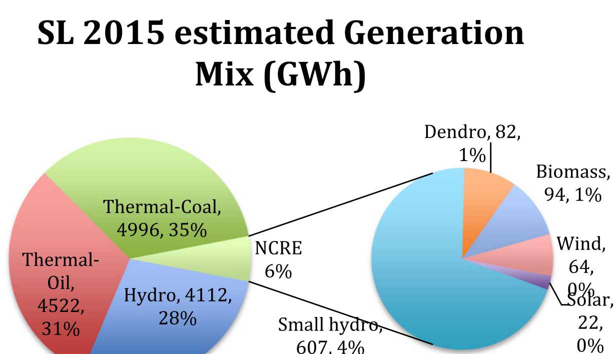

Fig. 4 SL 2015 estimated capacity mix [29–50]

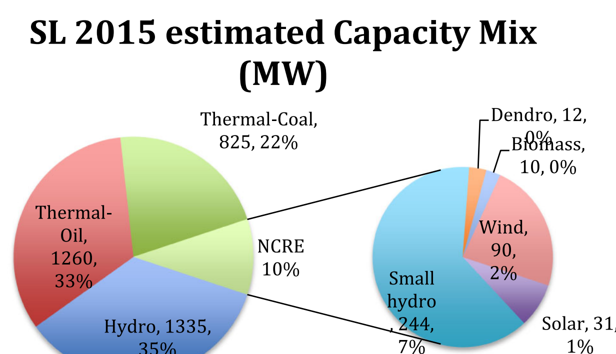

Fig. 5 SL 2015 estimated generation mix [29–51]

widespread, but it is gaining momentum [54]. As of 31/12/2014, 2 Agricultural and Industrial Waste Power projects have been commissioned (11 MW); and another 2 Dendro Power (5.5 MW) [55]. A 1000 MW of Dendro thermal potential has been estimated [59]. Biofuels are also planned to be developed to claim a 20 per cent share by 2020 [58, 62]. Although the village biogas power is at an early stage, as it has not been an easy task to introduce it [63, 64], there are indeed a number of projects going on. This NCRE seems to be following the increasing tendency currently shown in South Asia [59]. A 300 MW MSW biogas generation potential has been identified [65].

As showed on Table 6 above, the use of SHSs has been spreading fast in the rural areas of Sri Lanka, mainly because of the financial incentives provided by the donor agencies, and also due to the aggressive marketing strategies of the SHS dealers in rural areas [66, 67]. As of 31/12/2013, 4 solar projects have been commissioned, totalling 1,4 MW. As of 31/12/2012, the installed PV capacity was 10.10 MWp [68]. Concerning geothermal energy resources, SL is still at a preliminary stage, although a 700–1300 MWe potential has been recently estimated. As a first step in the development, a USD 10 M investment would cover a site selection study, surface exploration at the most promising site followed by deep drilling, and commissioning of a 2 MW binary power plant if the wells are successful [69]. Regarding off-grid schemes, a pilot project was recently conducted to connect two village micro hydro power plants (10 and 20 kW) to the national grid. This pilot project has become instrumental in removing the technical, social, and legal barriers for grid interconnection. It is necessary, though, to review these fees structure and try to reduce them, taking into account the capacity of the project [70] and the potential funding [71–73]. The overall target for NCRE is to reach 10 % by 2016 and 20 % by 2020 [63]. Some authors are praising SLs NCRE implementation [64], while others believe that lack of financing instruments, along with high initial cost and lack of assurance of resource supply or availability are the main barriers for renewable technologies expansion in SL [65, 66]. Reaching the above mentioned targets is not just an environmental matter, but are related in one way or another to at least five other MDG [67, 74]:

1. Eradicate extreme poverty and hunger.
2. Achieve universal primary education.
3. Gender equality and empowering women.
4. Reduce child mortality.
5. Improve maternal health.

Taking into account all of the above, the authors have estimated that the following energy is considered to be substitutable in 2015 (see below Table 7).

The authors have defined the following variables:

– BT_I: biomass thermal, industrial.
– BT_H: biomass thermal, household.
– BT_{HE}: biomass thermal, health.
– BT_C: biomass thermal, commercial.
– LBF_A: liquid biofuel, agriculture.
– LBF_T: liquid biofuel, transport.

Table 6 2012 status of Sri Lanka off-grid energy technologies

Technology	Number of units installed	Capacity of a unit (KW)	Estimated total capacity (MW)	Number of households electrified	Number of units still in use (estimated)
Solar home systems (PV)	120,000	0.03–0.06	3.6	120,000	100,000
Village micro hydro power	300	3–50	4.5	10,500	80
Village dendro power	11	10–30	0.1	100	–
Wind home systems	30	0.25–3.0	0.007	30	–
Village biogas power	10	0.3–2.0	0.006	30	2
Pico hydro power	40	0.3–1.5	0.012	40	40
Total			8.2	130,700	

Data from Apergis and Payne [50]

Table 7 Substitutable energy in 2015 (ktoe)

	Electricity	LPG	Gasoline	Naphta	Avgas	Kerosene	Avtur	Diesel	Foil	Coal	Bagasse	Fwood
Agriculture								0.5	1.3			
Industries	74.5							12.8	27.1			
Transport			147.3					288.6	0.4			
Education	0.8											
Religious	1.3											
HH	85.7											
Hotels	4.2								1.2			
Street light	2.9											
Health	3.1								0.4			
Commercial	47.2							2.2	2.1			

- SH: small hydro.
- WPP: wind power plant.
- BEG: biomass for electricity generation.
- PV: photovoltaic electricity generation.
- MSW: municipal solid waste.

The restrictions for this case study have been established by the authors as per below:

A: Based on energy demand and RE real potential (in ktoe):

1. $LBF_A \leq 1.8$
2. $BT_I \leq 2148.9$
3. $LBF_T \leq 436.3$
4. $BT_H \leq 1.2$
5. $BT_{HE} \leq 0.4$
6. $BT_C \leq 432.1$
7. Electricity[4]:

$$SH + PV + WPP + MSW + BEG \leq 219.8 \quad (22)$$

8. $SH \leq 150$
9. $PV \leq 30$
10. $WPP \leq 100$
11. $MSW \leq 100$
12. $BEG \leq 60$

B: Based on the already existing RE (in ktoe):

1. $LBF_A, LBF_T \geq 0$
2. $BT_I \geq 2109$[5]
3. $BT_H \geq 0$
4. $BT_{HE} \geq 0$
5. $BT_C \geq 427.8$
6. $SH \geq 47.3$
7. $PV \geq 3.6$
8. $WPP \geq 8.6$
9. $MSW \geq 0$
10. $BEG \geq 15.1$

To determine the coefficients corresponding to function F_1, the authors have established the precedence constraints included below in Table 8.

The following values are then calculated (see Table 9 below):

$$M_{ij} = \Pi_{i=1}^{n} a_{ij} \quad (23)$$

$$N_{ij} = \Pi_{i=1}^{n} \left(6 - a_{ij}\right) \quad (24)$$

Once the coefficients are applied, this is the final equation for F_1:

Table 8 Precedence constraints [54, 75–103]

	BEG	BT	LBF	MSW	PV	SH	WPP
Technological demand	2	2	2	3	4	5	3
Potential investigation	5	5	5	5	5	4	5
Know-how up-to-date	4	5	3	4	4	3	5
Technology improvement (possibly locally manufactured equipment)	3	3	3	3	3	3	2
Current technological level to apply the alternative energy	2	3	2	2			4
Operating time	3	5	2	3	3	4	2
Implementation issues	3	5	2	3	3	5	3
Integration possibility	5	5	5	5	5	5	5
Potential demand	2	2	2	4	4	5	4
Supply availability	3	3	2	4	4	4	4
Political interest	2	2	2	3	3	5	4
Current price compared with conventional energies	1	2	2	1	2	5	3
Social demand	1	2	1	2	2	5	2
Legislative forecast	3	3	3	3	3	3	3
Environmental impact	5	3	5	5	5	5	5

Table 9 Calculation of N and M factors

Alternative	M	N	Coefficient
SH	216	3.4×10^9	2.5
WPP	82,944	10^8	2.5
PV	186,624	9×10^7	2
BT	248,832	2.4×10^7	2
MSW	466,560	2.3×10^7	2
BEG	3.1×10^6	1.9×10^6	1.5
LBF	8,847,360	864,000	1

Source: own construction

$$F_1 = 2.5\ SH + 2.5\ WPP + 2\ PV + 2\ BT_I + 2\ BT_H + 2\ BT_{HE} + 2\ BT_C + 2\ MSW + 1.5\ BEG + LBF_A + LBF_T$$

Environmental impact minimization

CEB expected generation system for 2015 [20] has been taken into account (see below Table 10) to establish the potentially avoided emissions. According to the different types of fuel and their corresponding GWh in 2015, a 9.9 tCO_2/toe weighted average will be considered as the

[4] Electricity is studied separately as per its special characteristics. To avoid being over-optimistic, a maximum 20 % has been considered, having in mind that this percentage is expected by 2020 [47].

[5] Includes coal, bagasse and fuel wood as per Table 1.

Table 10 Generation forecast data from the Long Term Generation Expansion Plan 2013–2032, prepared by the CEB [20]

	Capacity balance (MW)			Energy balance (GWh)		
	2013	2014	2015	2013	2014	2015
Plant name						
Hydro						
Existing major hydro	1335	1335	1335	4112	4112	4112
New major hydro	0	0	0	0	0	0
Mini hydro	219	232	244	–	–	–
Sub total	1554	1567	1579	4112	4112	4112
NCRE-wind	90	90	90	–	–	–
NCRE-solar	1.3	21	31	–	–	–
Total NCRE				613	658	692
Thermal existing and committed						
Small gas turbines	85	85	85	16	6	4
Diesel Sapugaskanda	72	72	72	459	431	456
Diesel ext. Sapugaskanda	72	72	72	491	485	487
Gas turbine no 7	115	115	115	290	250	286
Lakdhanavi	0	0	0	0	0	0
Asia power	49	49	49	334	309	332
KPS combined cycle	165	165	165	550	454	549
AES combined cycle	163	163	163	491	362	474
Colombo power	60	60	0	419	417	0
ACE power Horona	0	0	0	0	0	0
Ace power Matara	0	0	0	0	0	0
Heladhanavi	100	100	0	696	696	0
ACE power Embilipitiya	100	100	0	692	672	0
Biomass (Dendro)	10	10	10	94	94	94
Kerawalapitiya	270	270	270	1325	935	1138
Puttalam coal	275	550	825	1665	3241	4996
Northern power	0	20	20	0	131	137
Chunnakkam power extension	0	24	24	0	183	183
Sub total	1535	1854	1870	7523	8668	9135
New thermal plants						
Coal	0	0	0	0	0	0
Gas turbine 75 MW	0	0	225	0	0	477
Gas turbine 105 MW	0	0	0	0	0	0
Coal trinco	0	0	0	0	0	0
Biomass (Dendro)	4	8	12	27	54	82
Sub total	4	8	237	27	54	559
Total installed capacity	3184	3540	3807	–	–	–
Installed capacity without NCRE[a]	2874	3197	3442	–	–	–
Peak demand	2451	2692	2894	–	–	–
Difference without NCRE[a]	423	505	548	–	–	–
Difference (%)	17.3	18.8	18.9	–	–	–
Total generation	–	–	–	12,275	13,493	14,499
System demand	–	–	–	12,296	13,508	14,513
Unserved energy				21	15	14

[a] This installed capacity does not include the non-dispatchable NCRE, i.e., mini-hydro, wind and solar

amount of avoided emission as well as 0.028 tNO_x/toe and 0.041 tSO_2/toe [20, 104–114].

You can find below Table 11, which includes a summary of the life cycle emissions corresponding to the different types of renewable energy, based on the below mentioned references.

In terms of LBF, 90 % of the CO_2 emissions are considered to be potentially avoided [122–124] that is, approximately 2.7 tCO_2/toe. When biofuel replaces gasoline and diesel in the transport sector, SO_2 emissions are reduced, but changes in NOx emissions depend on the substitution pattern and technology. The effects of replacing gasoline with ethanol and biodiesel also depend on engine features. Biodiesel can have higher NOx emissions than petroleum diesel in traditional direct-injected diesel engines that are not equipped with NOx control catalysts [125]. This is why no NOx avoided emissions have been taken into account. A 50 % average SO_2 emissions reduction is however considered, as the avoided emissions will depend very much on the blend.

Please find below de corresponding functions:

$F_2 = 9.78\ \text{SH} + 9.78\ \text{WPP} + 9.44\ \text{PV} + 9.27\ \text{BT}_\text{I} + 9.27\ \text{BT}_\text{H} + 9.27\ \text{BT}_\text{HE} + 9.27\ \text{BT}_\text{C} + 8.9\ \text{MSW} + 9.38\ \text{BEG} + 2.7\ \text{LBF}_\text{A} + 2.7\ \text{LBF}_\text{T}$

$F_3 = 0.028\ \text{SH} + 0.028\ \text{WPP} + 0.026\ \text{PV} + 0.02\ \text{BT}_\text{I} + 0.02\ \text{BT}_\text{H} + 0.02\ \text{BT}_\text{HE} + 0.02\ \text{BT}_\text{C} + 0.028\ \text{MSW} + 0.02\ \text{BEG}$

$F_4 = 0.04126\ \text{SH} + 0.0407\ \text{WPP} + 0.038\ \text{PV} + 0.041\ \text{BT}_\text{I} + 0.041\ \text{BT}_\text{H} + 0.041\ \text{BT}_\text{HE} + 0.041\ \text{BT}_\text{C} + 0.04128\ \text{MSW} + 0.041\ \text{BEG} + 0.0058\ \text{LBF}_\text{A} + 0.0058\ \text{LBF}_\text{T}$

F_5: Cost minimization of substitution of RE for existing conventional energy

Based on the typical capital cost ranges for RE power generation technologies, USD/kW [49, 137–139], the overnight capital cost is calculated (USD/toe) so that the appropriate coefficients can be applied:

$F_5 = 0.08\ \text{SH} + 0.32\ \text{WPP} + 0.3\ \text{PV} + 0.18\ \text{BT}_\text{I} + 0.14\ \text{BT}_\text{H} + 0.18\ \text{BT}_\text{HE} + 0.14\ \text{BT}_\text{C} + 0.48\ \text{MSW} + 0.55\ \text{BEG} + 0.94\ \text{LBF}_\text{A} + 0.94\ \text{LBF}_\text{T}$

It must be noted that a CHP use has been assumed for MSW biogas plants and LBF production.

F_6: Maximization of the most rural development friendly types of RE, aiming to improve health and education

See below Table 12, where the precedence constraints have been evaluated by the authors as per the below mentioned subjects, based on the indicated references.

M and N are then calculated as per Eqs. (23) and (24) (see Table 13 below):

Table 11 RE life cycle CO_2 emissions; tCO_2/toe, tNO_x/toe, tSO_2/toe [109, 112–121]

Life cycle emission	SH	WPP	PV	BT	MSW	BEG
CO_2	0.12	0.12	0.46	0.63	1	0.52
NO_X	0.00006	0.0004	0.0017	0.0083	0.00009	0.0083
SO_2	0.00003	0.0005	0.003	0.00042	0.000015	0.00042

Table 12 Precedence constraints [126–136]

	P and SH	SW	B	PV	LBF	MSW
Identified ad hoc applications	5	4	5	5	5	1
Low overnight capital cost/ unnecessary donor support	2	3	5	1	1	1
Low maintenance cost	4	5	4	5	1	1
Unnecessary maintenance contract	4	1	5	4	1	1
Long lasting systems	5	4	4	4	4	5
Short distance from energy source	4	5	5	5	2	1
Safe from being stolen in rural environment	4	4	3	1	5	5
Low rural environmental impact	3	5	2	5	2	2
Predictability	4	2	4	2	4	5
Batteries not required	2.5	1	2.5	1	2.5	2.5
AC	2.5	2.5	2.5	1	2.5	2.5
Possible rural modularity	1	2.5	1	2.5	1	1
Added benefits for rural development	1	1	1	1	1	2.5
In-country development	5	3	3	1	5	5
Low LEC	4	4	3	1	1	1
Space efficiency for rural Environment	1	4	1	3	1	1
Low waste generation	2.5 s	2.5	1	2.5	2.5	1

Table 13 Calculation of *N* and *M* factors

Alternative	*M*	*N*	Coefficient
P and SH	4.1×10^6	4.8×10^7	2.5
SW	6.2×10^6	3.6×10^7	2.5
B	6.6×10^6	1.35×10^7	2
PV	4.6×10^7	4×10^5	2
LBF	2×10^8	10^5	1.5
MSW	3.3×10^8	19,531	1

Own construction

Table 14 Optimization results using Matlab® programming tools

Weights	SH	WP	PV	BT_I	BT_H	BT_{HE}	BT_C	MSW	BEG	LBF_A	LBF_T
1,1,1,1,1,1[a]	86.7	43.2	3.6	2146.4	1.1	0.4	431.8	62.3	15.1	1	180.1
1,0,0,0,0,0	125.9	75.2	3.6	2148.9	1.2	0.4	432.1	0	15.1	1.8	436.3
5,1,1,1,1,1	109.1	61.7	3.6	2148.9	1.2	0.4	432.1	30.2	15.1	1.5	325.1
0,1,0,0,0,0	125.2	75.9	3.6	2148.9	1.2	0.4	432.1	0	15.1	1.8	436.3
1,5,1,1,1,1	104.4	58.1	3.6	2148.7	1.2	0.4	432.1	37.8	15.1	1.4	300.8
0,0,1,0,0,0	78.3	36.3	3.6	2148.9	1.2	0.4	432.1	86.5	15.1	0.9	114.7
1,1,5,1,1,1	86.7	43.5	3.6	2148.8	1.2	0.4	432.1	70.7	15.1	1.1	173.7
0,0,0,1,0,0	47.3	86	3.6	2148.9	1.2	0.4	432.1	14.5	15.1	1.8	436.3
1,1,1,5,1,1	95.5	50.7	3.6	2148.8	1.2	0.4	432.1	54.4	15.1	1.3	247.1
0,0,0,0,1,0	47.3	8.6	3.6	2109	0	0	427.8	0	15.1	0	0
1,1,1,1,5,1	61.2	20.8	3.6	2121.1	0.4	0.1	429.1	18	15.1	0.4	66.7
0,0,0,0,0,1	125	76.1	3.6	2148.9	1.2	0.4	432.1	0	15.1	1.8	436.3
1,1,1,1,1,5	112.6	64.6	3.6	2148.8	1.2	0.4	432.1	23.5	15.1	1.6	348.3
1,5,5,5,1,1	104.3	58.2	3.6	2148.9	1.2	0.4	432.1	38.4	15.1	1.4	299.1
5,1,1,1,1,5	112.6	64.4	3.6	2148.8	1.2	0.4	432.1	23.6	15.1	1.6	349.7

Own construction

[a] Weights have been indicated as per functions vector (F_1, F_2, F_3, F_4, F_5, F_6)

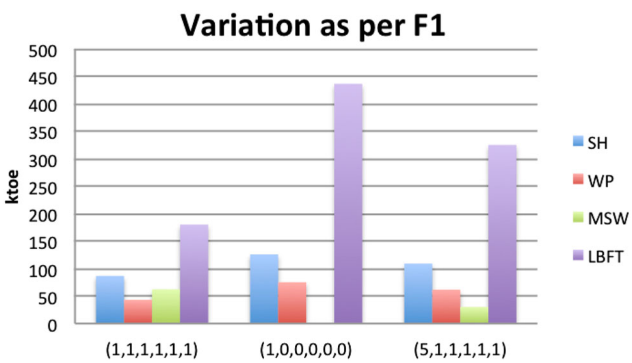

Fig. 6 SH, WP, MSW and LBF_T variation as per the weights assigned to function 1. Source: own construction

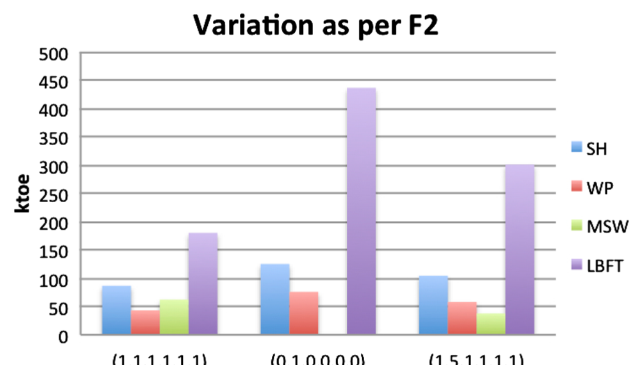

Fig. 7 SH, WP, MSW and LBF_T variation as per the weights assigned to function 2. Source: own construction

Once the coefficients are applied, this is the final equation for F_6:

$$F_6 = 2.5\,SH + 2.5\,WPP + 2\,PV + 2\,BT_I + 2\,BT_H + 2\,BT_{HE} + 2\,BT_C + MSW + 2\,BEG + 1.5\,LBF_A + 1.5\,LBF_T$$

Results and discussion

Please find below Table 14 and Figs. 6, 7, 8, 9, 10 and 11, which include the results obtained (in ktoe), using the Chebyshev distance, $L\infty$, following the Anti-Ideal Compromise Programming as previously defined in chapter 2.3; taking into account the below mentioned weights.

The authors have aimed to compare the solution obtained given no special weight to any of the functions: (1,1,1,1,1,1); with the obtained values when only one of the functions is taken into account: for example (1,0,0,0,0,0); and finally with the outcome solution when a special weight has been given to a particular function: for example (5,1,1,1,1,1). This way, the different solutions will clearly show the tendency the variables follow, when a particular function is given more importance than the others. The authors have added two more cases to this list, one giving special importance to the three emissions functions (F_2, F_3,

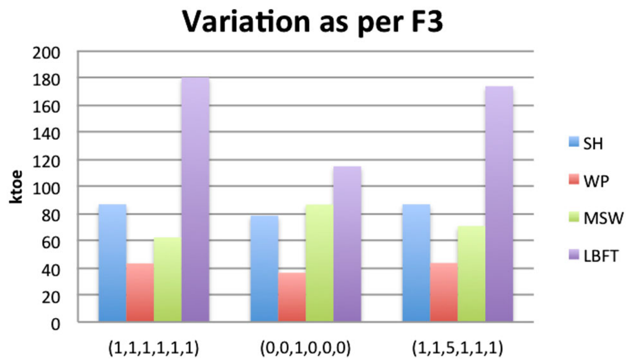

Fig. 8 SH, WP, MSW and LBF_T variation as per the weights assigned to function 3. Source: own construction

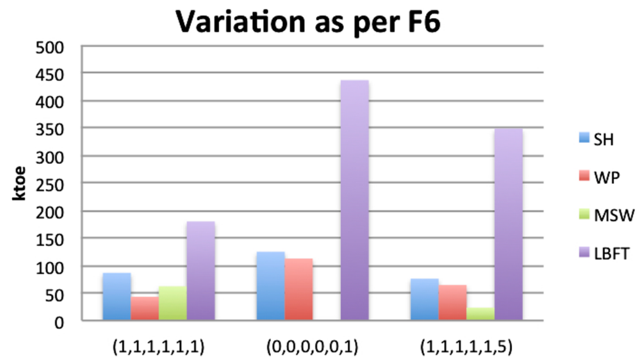

Fig. 11 SH, WP, MSW and LBF_T Variation as per the weights assigned to function 6. Source: own construction

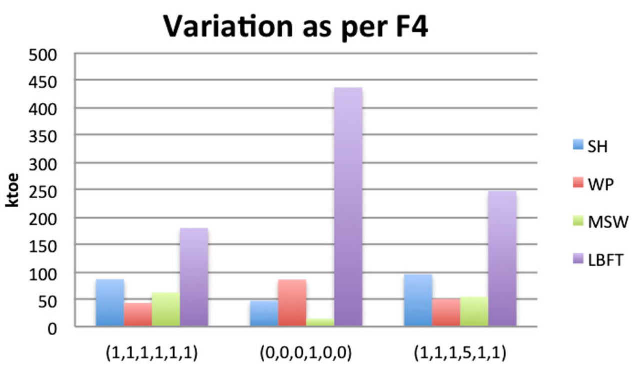

Fig. 9 SH, WP, MSW and LBF_T variation as per the weights assigned to function 4. Source: own construction

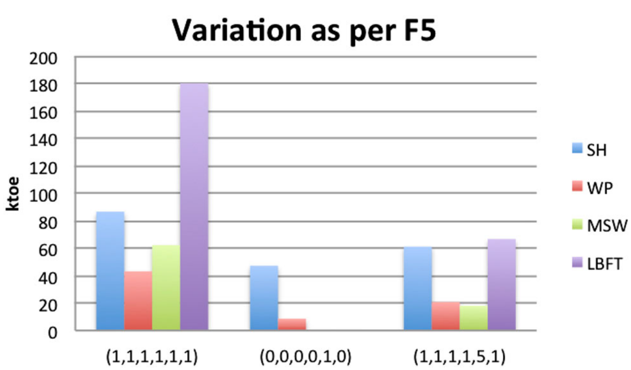

Fig. 10 SH, WP, MSW and LBF_T variation as per the weights assigned to function 5. Source: own construction

F_4), and another one targeting the maximum renewable energy substitution and rural health and education development (F_1 and F_6).

The nominal weights (1,1,1,1,1,1) are considered as the baseline. Once this baseline is obtained, then the other cases will be taken into account to give some special relative importance to any of the six functions or even to address some different weights to be applied if necessary [15, 16, 23, 24]. The results show that PV and BEG stay at their minimum potential value independently of the chosen weights, while the four biomass variables (BT_I, BT_H, BT_{HE} and BT_C) reach approximately their maximum potential value, except for the two cases where the economic factor is given a certain weight versus the other functions. This exception is totally expected, as function F_5 will always look for the cheapest solution, i.e., the one implementing less renewable energy substitution. The rest of the variables, SH, WP, MSW LBF_A and LBFT do vary, depending on the chosen weights. The first three variables are linked together as per Eq. (22). This means that any variation in one of them, will therefore affect the other. As can be seen in Figs. 6, 7, 8, 9, 10 and 11 above, when only one function is optimized, a maximum polarized value is obtained for the different variables. Once all six functions are taking into account, even if a weight 5 is applied to a particular one, the difference from the nominal results [the ones obtained as per (1,1,1,1,1,1)] is less acute, flattening this way the value given to the different variables.

If the individual optimizations [for example: (1,0,0,0,0,0)] are not considered, and the last two cases or also not taken into account, the maximization of the above mentioned variables may be summarized as per Table 15 below.

The authors have summarized below in Table 16 the advantages of applying this energy planning model to Sri Lanka, and also the potential improvements in Table 17.

Conclusions

This paper shows the possibility of using MCDM methods, focusing on a sustainable and renewable energy approach. The resulting energy models give a great level of importance to the human environmental development factors, avoiding, therefore, the purely economic reasoning. These type of models are becoming a common way of choosing global energy plans [139] or some independent power

Table 15 Maximization of SH, WP, MSW, LBF_A and LBF_T

Renewable energy	Reaches maximum value when prioritizing
SH	F_6 (max rural development) $> F_1 > F_2 > F_4 > F_3 > F_5$
WP	F_6 (max rural development) $> F_1 > F_2 > F_4 > F_3 > F_5$
MSW	F_3 (max NOx avoided emissions) $> F_4 > F_2 > F_1 > F_6 > F_5$
LBF_A	F_6 (max rural development) $> F_1 > F_2 > F_4 > F_3 > F_5$
LBF_T	F_6 (max rural development) $> F_1 > F_2 > F_4 > F_3 > F_5$

Own construction

Table 16 Advantages of SRIME application in Sri Lanka

SRIME singularity	Advantage for Sri Lanka
Multi-objective (6 equations)	Avoiding this way, single-objective financial perspective, which gradually would make SL poorer and more dependent on oil import
Takes into account CO_2 and also NO_x and SO_2	Automobiles are very contaminant in SL, NO_x is therefore of great importance
Maximizing RE	SL has proofed to be a fast RE growing country, improving industry in general
Health and Education equation	Very innovative precedence constraints application, aiming to set a sustainable growth through energy universal access
Possibility of applying weights	This way planners may choose which either if all objectives may have the same weight or there is a particular equation that must be given a certain priority
Pareto optimal solution	Assuring the chosen solution is not 'dominated' by any of the equations

Own construction

plants, such as wind farms [140]. This work has aimed at establishing a potential energy model implementation methodology that may be applicable for developing countries. The Case Study shows that if SRIME was implemented in Sri Lanka, SH, WP, MSW and LBF_T would be specially benefited from the Pareto optimization, while PV and BEG would stay at their official future expected value [20], having no growth at all. The SRIME model could be relatively easily interpolated to other Asian tropical countries, due to the similar circumstances in terms of health an

Table 17 Potential Improvements for SRIME application in Sri Lanka

Potential Improvement	Advantage
Introduction of hybrid systems	Very efficient for remote rural materially underdeveloped areas, with highly flexible configurations, and currently undergoing a high level of implementation
Equations weights to be decided by an international team of specialists (energy planners, maintenance specialists, policy makers and politicians) including, of course, people from Sri Lanka	One of the most important processes of the SRIME is the weights assignation. Although these groups may have different points of view, and sometimes even opposite objectives: consensus is a must

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education low overall parameters, high biomass consumption, monsoon special weather characteristics, low GDP and extremely high petroleum imports dependency.

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