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ANALYSIS OF SOLAR COOKER WITH THERMAL STORAGE FOR REMOTE HILLY AREAS: DETERMINATION OF HEATING AND COOLING CHARACTERISTIC TIME

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Abstract
Solar cooking finds a major application in rural areas of Uttarakhand, India, yet its utilization is still limited due to certain limitation such as intermittent nature of solar radiations. This drawback limits solar cooker in becoming a viable alternate solution of LPG and other pollution causing resources such as wood. In order to cater this problem a numerical analysis of box type solar cooker with storage is carried out. The energy stored in the storage material will keep the cooker warm up to the time when food is consumed. Charging and discharging time analysis is performed in with an aim to understand the effect of storage on solar cooker. Heating and cooling characteristic time are being evaluated and analysed with storage. Thermal performance of box type solar cooker is measured in terms of figures of merit according to BIS standards. The effect of storage has also been analysed in terms of charging and discharging time and first figure of merit of box type solar cooker.it has been observed that during discharging the heat is stored for more duration as compared to the charging time as discharge time is approx. 4-5 hours while charging time for the same amount of insolation is around 3-4 hours.

Keywords
solar energy, solar cooker, thermal storage, thermal performance

Introduction

One of the most energy-consuming sectors is cooking. In cooking the main energy used is kerosene, liquefied petroleum gases (LPG), biogas or wood. However, this energy damages the environment with pollution or deforestation and cause 1.6 million deaths per year (World health organization]. A lot of literature reported in the different aspects of performance analysis of solar cooker reveals that the thermal performance testing is one of the most prominent aspect of box type solar cooker.
Nevertheless, there exists an alternative with the sun. In several countries, there is an abundant solar radiation with daily solar energy in the range of 5-7 kWh/m² and number of clear sunny days per year. The advantages are clean energy, non-pollutant, no emissions, and low running costs [1].
The solar cooker is also the ideal candidate to solve this problem and there are different types of solar cookers available for cooking.
A lot of research was focused on improving their efficiencies of various types of solar cookers such as concentrating type, parabolic, panel solar cookers, cookers with variation in shapes or geometry as square and rectangular and cookers with storage.
The first thermal performance analysis was led by Volunteers in Technical Assistance (VITA) [2], the evaluation was on different measures, for example, cooking execution, strength, cost.

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Various parametric performance analysis of solar cooker can be fetched from literature review [3–5]. The literatures reviewed are helpful during the design and development of solar cookers according to the demographic conditions.
Different techno monetary psychological factors scaled on 100 pointer scale were evaluated by an examination announced by Bowman and Blatt [6], transient model for a single glazed box type solar cooker was proposed by Garg et al. [7] predicted the temperature profile for various elements of the cooker. Certain improvements were added by Vaishya et al. [8] in a box type solar cooker.
A concentrating-type cooker is composed of multifaceted mirrors, Fresnel lens, and parabolic or spherical collectors to reach higher temperatures. Generally, this cooker can be designed with one or two axis-tracking systems to follow the course of the sun to determine the optimal angle of reflector which varies at every hour, that's why this oven can be equipped of point tracking (MPPT) techniques like a solar panel [9,10].
The principle of non-focusing type cookers is based on a heat transfer fluid that carries thermal energy until an oven. Simply, the fluid is heated by the solar radiation then the fluid heats the oven. This is the same principle as solar heating. This category is more useful for indoor cooking application nevertheless it is more expensive to produce [10].
A box-type solar cooker is composed of an insulated box with a transparent glass cover (generally double glazing). The absorber part is usually made up of material with a high conductivity and painted black to increase the sunlight absorption and reduce reflection. The temperature of a solar box cooker can be raised to around 100°C but like each component of the box has a significant influence on cooking power, the temperature can be higher than 100° C [1,10].
A different sub-category of cooker which can equip the three previously cooker are the direct-type solar cooker receiving direct solar radiation. The indirect cooker uses a heat transfer fluid to transfer the energy from the collector to the cooking unit. Classic cookers can be equipped with one or two-axis-tracking systems to follow the sun [10].
Geddam et al. [11] worked on experimental analysis and obtained F2 using a test procedure to determine these parameters under different load conditions of water. The procedure is used to generate heating characteristic curves of the solar cooker. Manuel et al. [12] proposed a revision and formulated the revision in the existing standards.
Even if the solar cooker is used to cook food, its biggest problem is if there is insufficient or no sunshine, the cooker does not work that is why storage can be added to the cooker. This addition of thermal storage will help in keeping the solar cooker hot for an extended amount of time, after the sunset. This work focusses on the study of a mathematical model to find the temperature of the storage and determine the characteristic time of heating and cooling of this storage integrated with box type solar cooker. The performance has been evaluated considering the solar cooker with and without storage.

Methods

Theoretical model of the solar cooker without storage

In his article [6], Mullick determines the balance energy of a box-type solar cooker:

$$\eta_0 \, H_S = U_L \left(T_{ps} - T_{as}\right) \quad (1)$$

where:

- η_0 is the optical efficiency calculated with the absorption of each wall.
- H_S the insulation on a horizontal surface
- U_L the heat loss factor, a method to calculate this factor will be explained in the next part.
- T_{ps} the plate stagnation temperature
- T_{as} the ambient stagnation temperature

He determines the first figure of merits:

$$F_1 = \frac{T_{ps} - T_{as}}{H_S} = \frac{\eta_0}{U_L} \quad (2)$$

It is obtained by keeping the solar cooker without vessels in the sunshine in the morning between 10 am and 2 pm.

This parameter allows to determine the performance of an empty solar cooker which is considered good when:

$$0.12 < F_1 < 0.16$$

Mullick describes another parameter: the second figure of merits F_2 which determines the performance of a full solar cooker and depends on the load and the number of the pots inside the cooker [5].
F_2 is independent of climatic variables and is dimensionless. it is considered good when:

$$0.254 < F_2 < 0.490$$

Theoretical model of the solar cooker

The MNRE Model of box type solar cooker is considered for analysis.

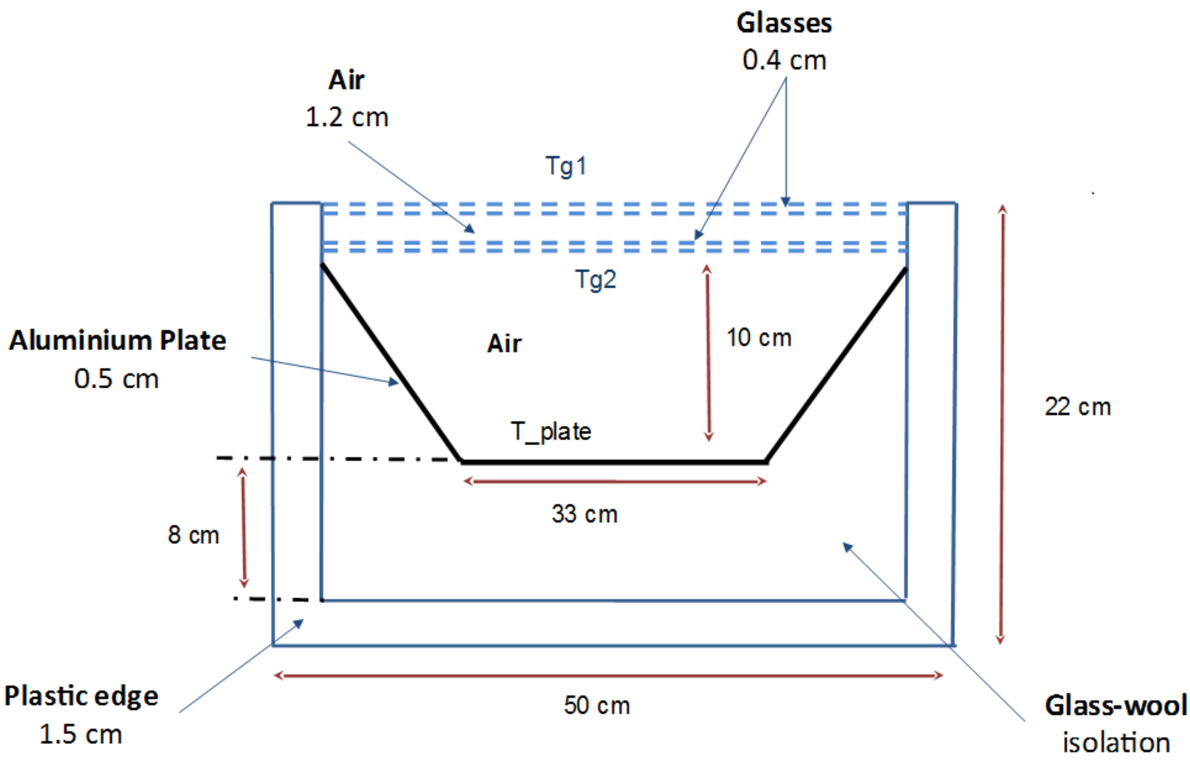

Fig. 1. Schematic of box type Solar cooker

The ambient temperature is assumed to be $T_a = 35°C$.

Since convection coefficients are necessary to evaluate flows between walls, these coefficients are calculated by using various correlation.
The following expressions are calculated at the interface temperature T_m.
.
First, the Rayleigh number is needed:

(3)
$$Ra = \frac{g\, \beta\, (T_p - T_\infty) L_C^3}{\nu^2}\, Pr$$

where :

- g is the gravitational acceleration
- $\beta = \frac{1}{T_m}$, here the air is considered as a perfect gas

- L_C the characteristic length
- the air Prandtl number $\mathrm{Pr} = 0.9257\, T_m^{-0.0457}$
- the air dynamic viscosity $\nu = 8.03 \times 10^{-10}\, T_m^{1.7354}$

The Nusselt number for a rectangular closed cell should be calculated with:

(4)
$$Nu = 1 + 1.44\left(1 - \frac{170}{Ra}\right) + \left[\left(\frac{Ra}{5830}\right)^{\frac{1}{3}} - 1\right]$$

Then, the convective coefficient is equal to :

(5)
$$h = \frac{Nu\, \lambda}{L_C}$$

with:

- L_C the characteristic length
- λ the air conductivity $\lambda = 0.0002045\, T_m^{0.85}$

Expressions of λ, ν and Pr come from Duffie [2].
However, in natural convection, the wall temperatures are needed: T_{g1}, T_{g2}, and T_p.

<u>Determination of glasses and plate temperature</u>

The electrical analogy of Duffie is followed [2]:

with:

- the external radiation:

(6)
$$h_{r,a-g1} = \frac{\sigma\, \varepsilon_{g1}\left(T_{g1} + T_{sky}\right)\left(T_{g1}^2 + T_{sky}^2\right)\left(T_{g1} - T_{sky}\right)}{\left(T_{g1} - T_a\right)},\, T_{sky} \approx T_a$$

- the external convection:

(7)
$$h_{wind} = 5.7 + 3.8\, v$$

  v is the velocity of the air
- the radiation between the two glasses :

(8)
$$h_{r,g1-g2} = \frac{\sigma\left(T_{g1} + T_{g2}\right)\left(T_{g1}^2 + T_{g2}^2\right)}{\frac{1}{\varepsilon_{g1}} + \frac{1}{\varepsilon_{g2}} - 1}$$

- the convection between the two glasses is determined with the previous correlation, $\mathrm{h_{c,g1-g2}}$
- the radiation between the second glass and the plate:

(9)
$$h_{r,g2-p} = \frac{\sigma\left(T_{g2} + T_p\right)\left(T_{g2}^2 + T_p^2\right)}{\frac{1}{\varepsilon_{g2}} + \frac{1}{\varepsilon_p} - 1}$$

- the convection between the second glass and the plate is determined with the previous correlation, $h_{c,g2-p}$

The thermal resistance is:

(10)
$$R_1 = \frac{1}{h_{wind} + h_{r,a-g1}}$$

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(11) $$R_2 = \frac{1}{h_{c,g1-g2} + h_{r,g1-g2}}$$

(12) $$R_3 = \frac{1}{h_{c,g2-p} + h_{r,g2-p}}$$

the following resistance are for the conduction :

(13) $$R_i = \frac{e_i}{\lambda_i}$$

Now, the top loss heat coefficient can be calculated:

(14) $$U_t = \frac{1}{R_1 + R_2 + R_3}$$

The side and bottom loss heat coefficient are calculated with the sum of the conduction resistance:

(15) $$U_s = \frac{1}{R_{cond,s}} \text{ and } U_b = \frac{1}{R_{cond,b}}$$

The total heat loss is:

(16) $$U_L = U_t + U_s + U_b$$

Finally, temperatures are determined with:

(17) $$T_j = T_i + \frac{U_t\,(T_p - T_a)}{h_{c,i-j} + h_{r,i-j}}$$

The plate temperature will be calculated with the Mullick [13].

Theoretical model of the solar cooker with storage.

Different types of storage.
The storage unit in a solar cooker is also an important issue. Indeed to overcome the alternative aspect of the sun it could be interesting to add a storage unit at the solar cooker. The storage unit's goal is to store energy during a time that the user doesn't need it and redistribute it when the user will. It is a way to delay the time of energy availability and consumption. There are two main thermal energy storages: sensible heat and latent heat.
The sensible heat storage consists of warm-up a material (fluid or solid). The range of temperature during this operation does not include a phase change of the material. The heat stored in this material is given by equation $Q = m\,C_P\,\Delta T$.

On another hand, Latent heat storage use Phase Change Materials called $PCMs$. This storage method uses the chemical properties of $PCMs$. Indeed the heat could be stored is given by with the Latent heat of phase change. With this storage way, a large energy quantity is stored at the phase change temperature because ΔH_{12} is significantly bigger (around $10^6\,J.kg^{-1}$ for vaporization enthalpy of water) than specific heat ($10^3 Jkg^{-1}K^{-1}$). It is said that Latent heat storage has a capacity between 5 to 14 times more than Sensible heat storage, the equation is given by

(18) $$Q = m\,C_{p_{phase1}}\Delta T + m\,\Delta H_{12} + m\,C_{p_{phase2}}\Delta T$$ [8]

However, Latent heat storage begets a large volume variation in the opposite of sensible heat storage. Moreover, a sensible heat storage unit is easier to implement on a cooker. The storage material must be chosen according to some criteria based on mechanical or thermal properties, availability, recyclability, price, etc. Some properties in the sensible heat storage material are important as thermal conductivity, density, and specific heat and diffusivity. Sensible heat storage materials can be classified into 4 groups [4].
Sensible heat storage is chosen for the rest of the study. A magnesia brick with a thickness of 50 cm is added in the initial cooker:

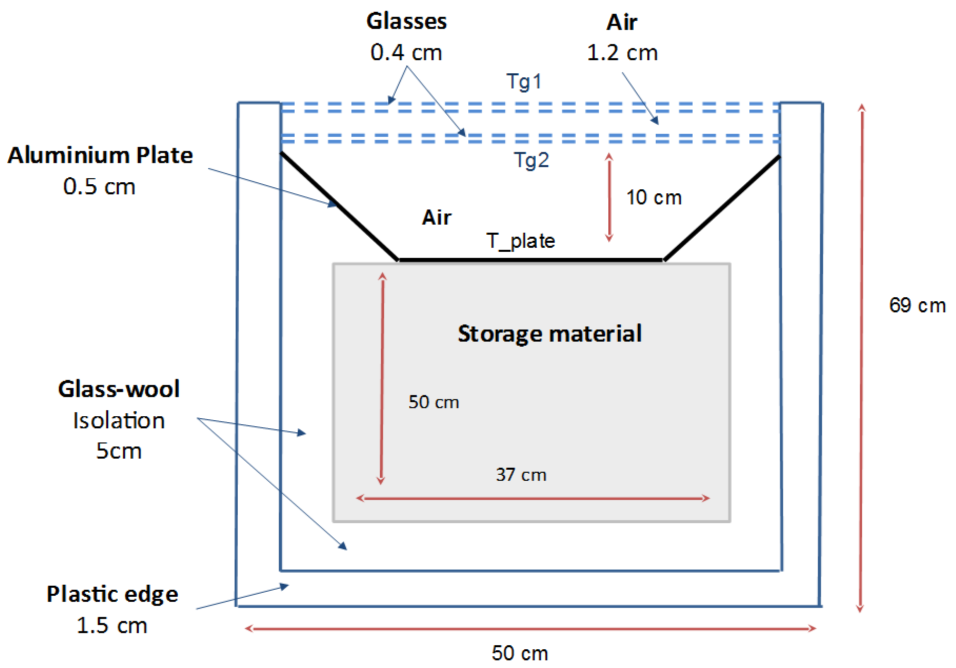

Fig. 2. Schematic of cooker with storage.

The goal of this part is to determine the characteristic time of heating and cooling of the brick. To simplify the problem, the magnesia brick will begin to heat when the plate is at its final temperature. The storage temperature is supposed constant on the surface and depends only on the thickness.
Only conduction is considered in the problem, the heat equation is also:

[19] $$\frac{\partial T_s}{\partial t} - a\,\frac{\partial^2 T_s}{\partial z^2} = \frac{p}{\rho\, C}$$

with the source term $p = \alpha_{g1} \times \alpha_{g2} \times \alpha_p \times \alpha_s \times S_s \times H_s$.

To solve this equation, the finite difference method is used and only the explicit method will be used [7]. After the discretization, a new system is obtained:

[20] $$B\, T^{n+1} = A\, T^n + k\, F$$

With:

[21] $$\begin{cases} A = \mathbb{I} + \dfrac{\alpha\, k}{h^2} \\ B = \mathbb{I} \end{cases}$$

And the rigidity matrix:

[22]

$$K = \begin{pmatrix} -2 & 1 & 0 & 0 & 0 & \cdots & 0 \\ 1 & -2 & 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & -2 & 1 & 0 & \cdots & 0 \\ & & & & & & \\ 0 & \cdots & \cdots & 0 & \ddots & \ddots & 1 \\ 0 & \cdots & \cdots & \cdots & 0 & 1 & -2 \end{pmatrix}$$

k is the time step and h is the space step. For the explicit method, $a\,\frac{k}{h^2} < \frac{1}{2}$, else the problem differs.
Now, the following vector can be built:

[23]

$$T^{n+1} = (B^{-1}\,A)^n\,T_0 + k\,B^{-1}\,\sum_{p=0}^{n-1}(B^{-1}\,A)^p\,F$$

The size of this vector is $\frac{L}{h}$ and the power n corresponds with the variation of the temperature about the thickness at a giving time. The following matrix will be built:

[24]

$$\begin{array}{cccc}
t = 1s & t = 2s & \cdots & t = ns \\
\downarrow & \downarrow & & \downarrow
\end{array}$$

$$\begin{pmatrix} T^1(z_1) & T^2(z_1) & \cdots & T^n(z_1) \\ T^1(z_2) & T^2(z_2) & \cdots & T^n(z_2) \\ \vdots & \vdots & \vdots & \vdots \\ T^1(z_{50}) & T^2(z_{50}) & \cdots & T^n(z_{50}) \end{pmatrix} \begin{array}{l} \leftarrow \quad L = 1\,cm \\ \leftarrow \quad L = 2\,cm \\ \qquad\quad \vdots \\ \leftarrow \quad L = 50\,cm \end{array}$$

For the charge, the typical solution is:

[25]

$$T_{ch}^{n+1} = T_0 - (B^{-1}\,A)^n\,(T_0 - T_a) + k\,B^{-1}\,\sum_{p=0}^{n-1}(B^{-1}\,A)^p\,F$$

with:
- T_0 is the stagnation temperature of the plate.
- T_a is the ambient temperature.

For the discharge, the source terms disappear, and the heat equation becomes:

[26]

$$\frac{\partial T_s}{\partial t} - a\,\frac{\partial^2 T_s}{\partial z^2} = 0$$

The type of solution is:

[27]

$$T_{dis}^{n+1} = T_a - (B^{-1}\,A)^n\,(T_a - T_0)$$

The evolution of temperature can be plotted at a given length:
For the cooling of the walls, the system becomes:

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[28]

$$\begin{cases} \dfrac{dT_{g1}}{dt} = \dfrac{T_{g1}(t)}{\tau_{g1}} - \dfrac{T_a}{\tau_{g1}} \\ \dfrac{dT_{g2}}{dt} = -\dfrac{T_{g1}(t)}{\tau_{g2}} + \dfrac{T_{g2}(t)}{\tau_{g2}} \\ \dfrac{dT_p}{dt} = -\dfrac{T_{g2}(t)}{\tau_p} + \dfrac{T_p(t)}{\tau_p} \end{cases}$$

The characteristic times don't change with the cooling.

Results and discussion

The determination of heating and cooling characteristic time of a solar cooker is carried out numerically and the results are discussed for the box type solar cooker with and without storage.

Solar cooker without storage

The calculation for the analysis is initiated by random selection of temperatures T_{g1}, T_{g2}, and T_p . Another plate temperature is defined by T_{pn}, and this value will be calculated in the loop. In the input data, this value must be different from T_p. This algorithm also calculates T_{g1}, T_{g2}, T_p, the convective and radiative coefficient of each wall and the heat loss coefficient. The program is feasible for different values of insulation and external air velocity, and the results obtained are summed in the following table 1.

Table 1. Heat loss analysis of a box type solar cooker without storage

H_S (W/m^2)	v (m/s)	T_{g1}	T_{g2}	T_p	h_{wind}	$h_{r,a-g1}$	$h_{c,g1-g2}$	$h_{r,g1-g2}$	$h_{c,g2-p}$	$h_{r,g2-p}$	U_L
400	1	44.6	75.2	100.0	9.50	19.87	2.70	6.52	2.47	8.88	4.50
	2	43.5	74.3	99.2	13.30	19.79	2.72	6.46	2.48	8.82	4.56
	3	42.7	73.6	98.6	17.10	19.73	2.73	6.42	2.48	8.78	4.61
600	1	49.3	91.0	123.7	9.50	20.27	2.97	7.28	2.48	10.56	4.98
	2	47.8	89.7	122.6	13.30	20.15	2.98	7.18	2.50	10.46	5.04
	3	46.5	88.7	121.8	17.10	20.10	3.00	7.11	2.51	10.39	5.08
800	1	53.9	105.3	144.3	9.50	20.66	3.12	7.99	2.49	12.18	5.39
	2	51.9	103.8	143.0	13.30	20.50	3.13	7.86	2.51	12.04	5.45
	3	50.2	102.5	142.0	17.10	20.36	3.16	7.76	2.52	11.94	5.50

The data obtained reveals that the temperature of the first glass is a significantly affected by the air velocity. Indeed, this temperature variation is due to the high intensity of forced convection which is cooling the glass surface. However, this convection does not affect the temperature inside the cooker as the velocity changes.
It is seen from the table that the wall temperatures rise with increase in the insulation and simultaneously the heat loss coefficient also raises.
Further, the first figure of merits can be calculated. For our system, the magnitude of the optical efficiency calculated is $\eta_0 = \alpha_{g1} \times \alpha_{g2} \times \alpha_p = 0.736$
The values *F1* obtained have been plotted across the plate temperature as shown in Fig. 3:

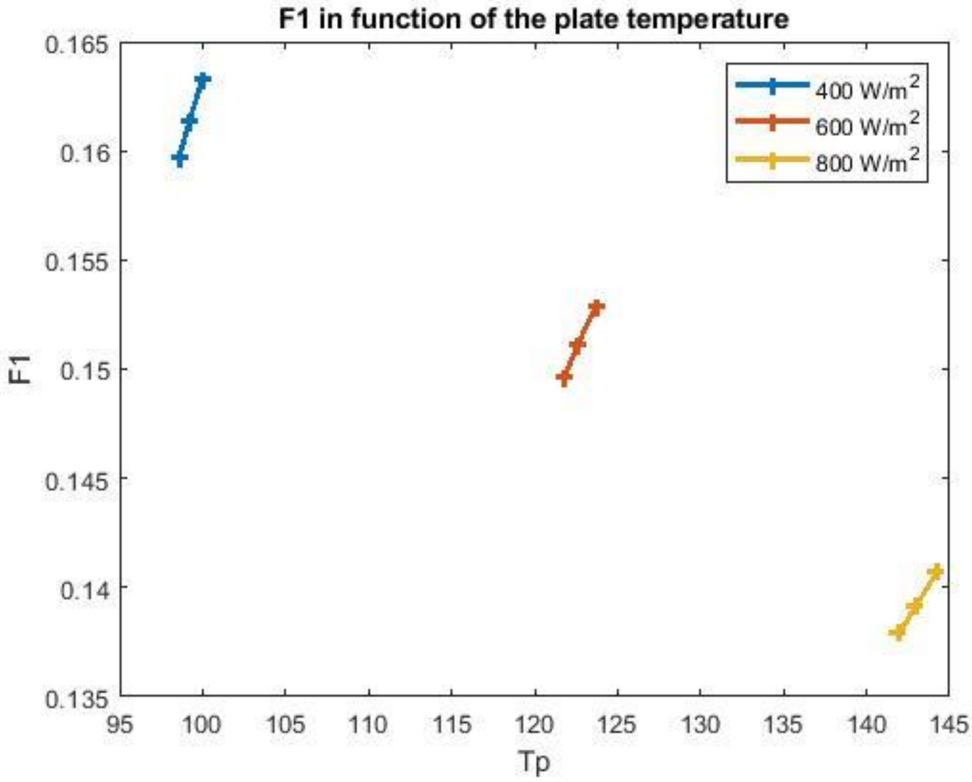

Fig. 3. Variation of F_1 first figure of merit with plate temperature of solar cooker without storage

It is seen in the figure that the values of the first figure of merit are obtained in the range of $0.1379 < F_1 < 0.1633$. Thus the present models selected are acceptable in terms of first figure of merit (*F1*). It is observed from the figure that an increase in the insulation magnitude lowers the value of first figure of merits. Whereas the higher value of insolation leads to higher plate temperature. It can be explained by the fact that as the temperature of the plate raises with insulation, there is an increase in the heat losses. As the convection current grows with the elevated wall temperatures, reduction in the thermal resistance is seen that leads to heat loss coefficient intensification.

Characteristic time of each element

The exchanges coefficients for a solar cooker have been calculated in the previous part with a permanent defined approach. Thus a transitory approach is described here. To simplify the heat equation, a calculation of the Biot number is made, with each wall having magnitude of $Bi \ll 1$, here the temperature inside each wall is considered to be isotherm. The energy balance equation becomes [2]:

[29] $$\rho\, C\, V\, \frac{dT_g}{dt} = Q_{exchange}(t) + Q_{source}(t)$$

Finally, the following system is obtained:

[30] $$\begin{cases} \dfrac{dT_{g1}}{dt} = -\dfrac{T_{g1}(t)}{\tau_{g1}} + \dfrac{T_a}{\tau_{g1}} + \dfrac{\alpha_{g1}\, H_s}{\left(h_{wind} + h_{r,a-g1}\right)\tau_{g1}} \\ \dfrac{dT_{g2}}{dt} = \dfrac{T_{g1}(t)}{\tau_{g2}} - \dfrac{T_{g2}(t)}{\tau_{g2}} + \dfrac{\alpha_{g1}\, \alpha_{g2}\, H_s}{\left(h_{c,g1-g2} + h_{r,g1-g2}\right)\tau_{g2}} \\ \dfrac{dT_{gp}}{dt} = \dfrac{T_{g2}(t)}{\tau_p} - \dfrac{T_p(t)}{\tau_p} + \dfrac{\alpha_{g1}\, \alpha_{g2}\, \alpha_p\, H_s}{\left(h_{c,g2-p} + h_{r,g2-p}\right)\tau_p} \end{cases}$$

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With the characteristic time:

[31]
$$\begin{cases} \tau_{g1} = \dfrac{\rho_g \, C_g V_g}{S_g\left(h_{wind} + h_{r,a-g1}\right)} \\ \tau_{g2} = \dfrac{\rho_g \, C_g V_g}{S_g\left(h_{c,g1-g2} + h_{r,g1-g2}\right)} \\ \tau_{g2} = \dfrac{\rho_p \, C_p V_p}{S_p\left(h_{c,g2-p} + h_{r,g2-p}\right)} \end{cases}$$

The results obtained for the characteristic time are summed up in Table 2, and the time unit selected is in seconds.

Table 2. Parametric analysis for different insolation conditions

H_s (W/m^2)	v (m/s)	τ_{g1} (s)	τ_{g2} (s)	τ_p (s)
400	1	245	781	1067
	2	218	784	1071
	3	196	787	1075
600	1	242	703	928
	2	215	708	934
	3	193	712	938
800	1	239	648	826
	2	213	654	832
	3	192	660	838

The entire wall is considered at the stagnation temperature when the timer reaches 5 τ and for the second glass and the plate, the characteristic time observed is constant for each air velocity at a given insulation condition. However, this characteristic time decreases with increase in insulation because the walls absorb more heat energy ($\alpha_{g1}\ \alpha_{g2}\ S\ H_s$ for the second glass and $\alpha_{g1}\ \alpha_{g2}\ \alpha_p\ S\ H_s$ for the plate). That is the reason for temperature elevation with insulation and corresponding characteristic time reduces.
In contrast, the first glass characteristic time depends on air velocity. Indeed, time drops with velocity because the temperature decreases when the velocity raises. The glass requires less energy as the velocity increases and in this condition the characteristic time is also weaker.

Analysis of solar cooker with storage
Charging and discharging analysis of box type solar cooker with storage has been carried out in this section.
It can be depicted from the figure 4 that the storage material used for storage of sensible heat is magnesia and it shows the variation of the temperature of the storage with respect to the different solar radiations and it shows that the temperature increases exponentially with respect to the time .and it becomes stagnant after certain duration due to the reason that the temperature gradient inside the storage among the different layers is reduced which decreases the heat transfer. While considering the discharging process the variation of storage temperature during discharging process has been explained in figure 5 and it can be seen that the temperature decreases exponentially initially and becomes stagnant after certain duration and the reason behind this is the temperature

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gradient and stratification are less, however along the length variation is more at initial layer during charging and the same has been depicted during discharge process.

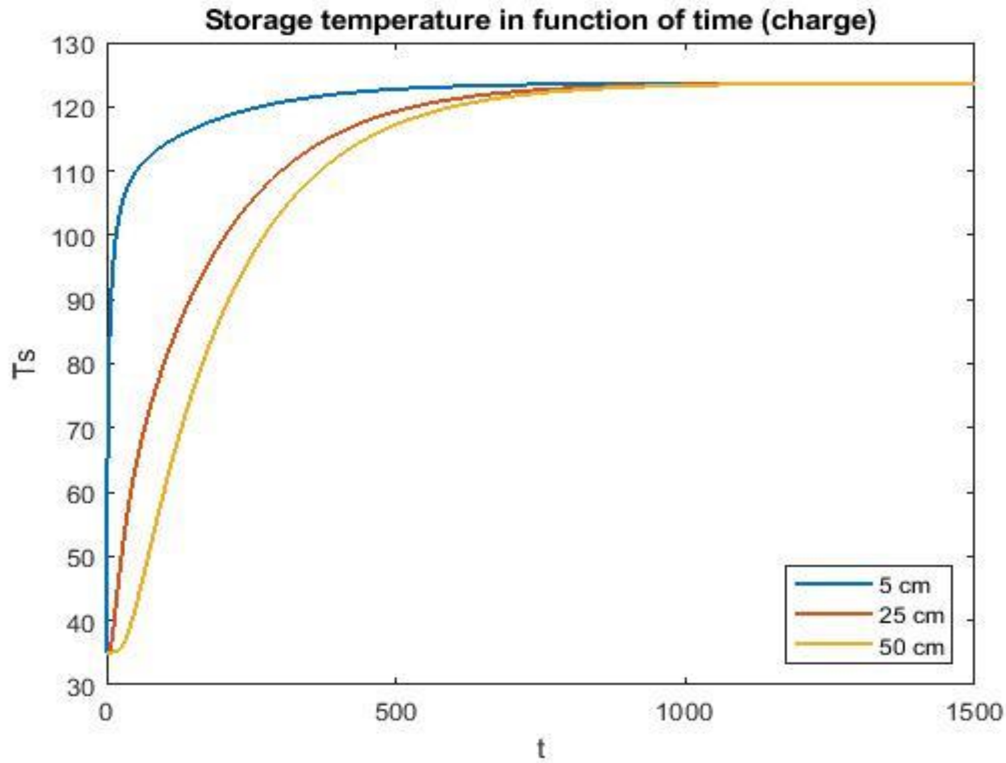

Fig. 4. Variation of storage temperature with time

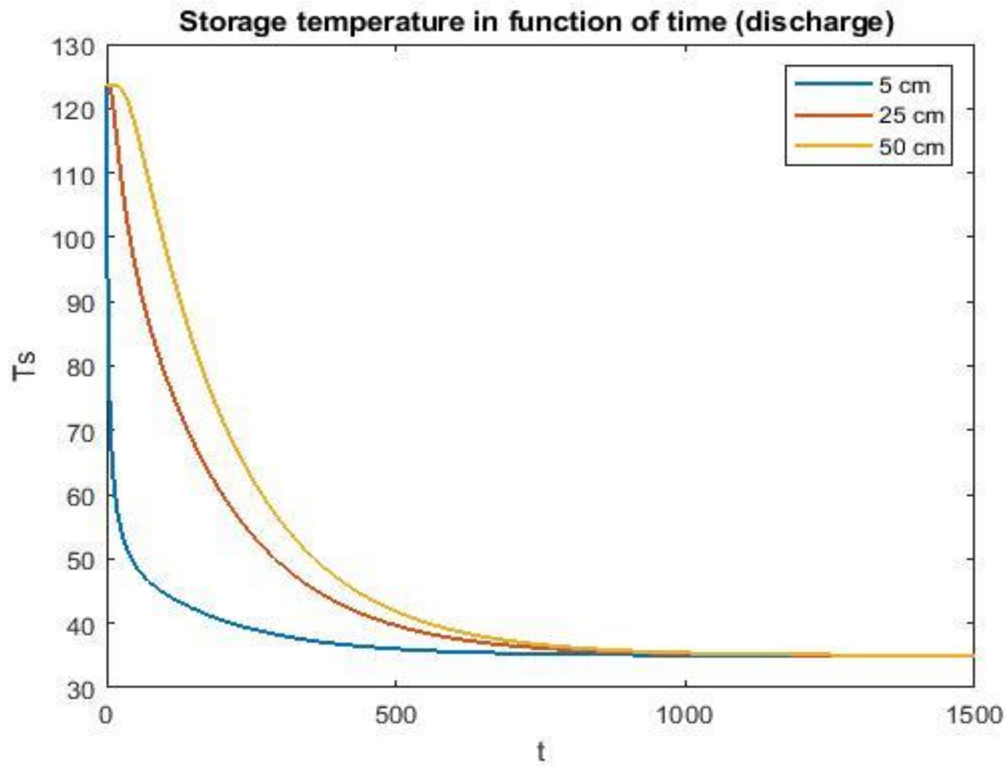

Fig. 5. Variation of storage temperature with time during discharging

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Charge and discharge analysis

For analysis purpose the storage system is divided in equal parts with a thickness of L/N. It is considered that the heat in the plate spreads by conduction and transfers its heat to the first layer of the storage material. Then, each layer dissipated its heat to the one at lower temperature until there is a stagnation plate temperature achieved by each layer. Each layer will take time to reach the stagnation temperature and the total charging time of the storage will be the sum of the time to reach the stagnation temperature by an individual layer. For calculating the total discharging time of the thermal storage system of solar cooker, the same approximation method is being used. The first layer will transfer its heat until the plate reaches the stagnation temperature, and there is no heat transfer because of same temperature.

For the charging phase, the total final time is considered when the temperature reaches 99% of the stagnation plate temperature. For the charging, the final time is considered when the temperature reaches 101% of the ambient temperature.

Table 3. Parametric analysis for different insolation conditions with storage in cooker

H_S $(^{W}/_{m^2})$	v (m/s)	t_{ch} (s)	$\mathrm{t_{ch}}$ (h:min)	$\mathrm{t_{dis}}$ (s)	$\mathrm{t_{dis}}$ (h:min)
400	1	12041	3:20	16193	4:30
	2	12026	3:20	16155	4:29
	3	12016	3:20	16121	4:29
600	1	12250	3:24	17145	4:46
	2	12241	3:24	17107	4:45
	3	12229	3:24	17082	4:45
800	1	12355	3:26	17791	4:56
	2	12353	3:26	17753	4:56
	3	12338	3:26	17724	4:55

It can be observed cooker has a great power storage because the case may be almost 5 hours. Charging times is practically constant whereas discharging times raise with insulation. The following graphs represent the first figure of merits across charging and discharging time:

It can be observed from the above figures 6 and 7 that the first figure of merit so the loss heat coefficient has a big influence on the charging and discharging.

For the charging duration, storage needs more time to keep energy when heat losses are high initially due to high temperature difference. But during the discharge of the cooker storage the discharge time is more which is more beneficial because the temperature difference between the plate and the storage are not very high therefore heat losses are high during charging phase but low during discharging.

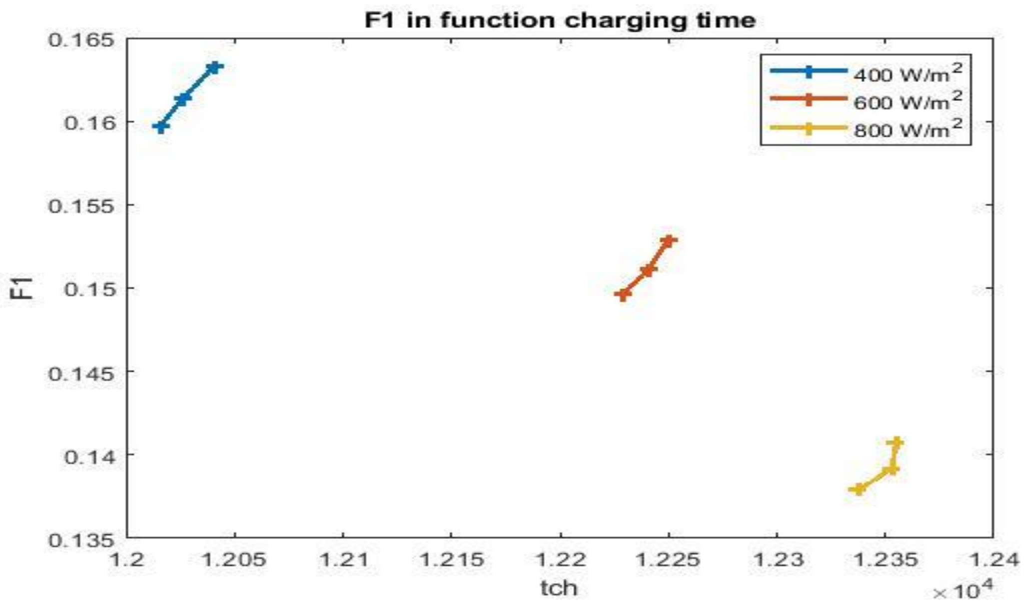

Fig. 6. Variation of first figure of merit with charging time

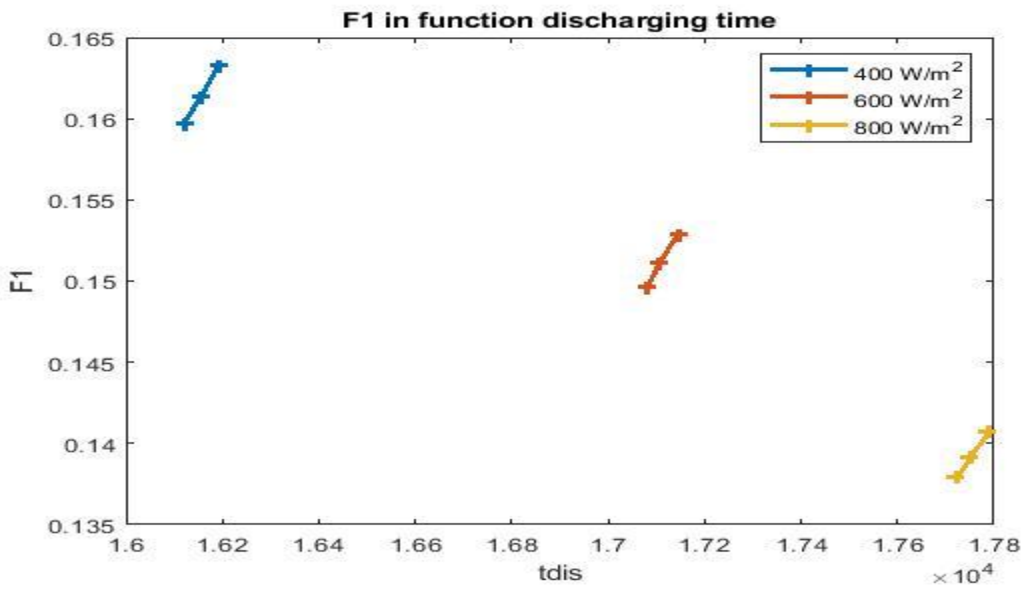

Fig. 7. Variation of first figure of merit during discharging

Impact

The present analysis of box type solar cookers is carried out to determine the thermal performance. The charging and discharging time characteristic of heat in the cooker is analysed in order to determine the time taken for each. Energy stored in the storage material will keep the cooker warm up to the time when food is consumed. The thermal performance of box type solar cookers is measured in terms of figures of merit according to BIS standards. The present novel idea of a box type solar cooker packed with the storage material is to store the thermal energy during charging time and discharge the heat during discharging, when there is no solar radiation. This cooker will keep the food warm for about 4-5 hours, thus saving fuel energy for heating the food again. There will be fuel saving and this will lead to the economic benefit of the people using this type of cooker. The novel cooker with storage design and fabricated will impact the economic condition in the rural area by saving money for cooking and reheating the food using fuel/LPG. This system will deliver an economic benefit by saving the fuel energy and have a deep impact on the environment by using a non-polluting source of energy.

Conclusion

A mathematical model of a solar cooker is proposed to determine convection and radiation coefficients. These coefficients allowed us to identify the wall temperatures and the characteristic times of each wall. The calculation of the first figure of merit permitted to show the good performance of the cooker, selected for study with storage. Then, a storage system was added, and modelling allowed to bring the possibility to use solar cookers during cloudy or after sun hours. The first figure of merit has also an influence of charging and discharging time benefits in a case and harmful in another.

The F1 has a significant effect on charging and discharging time while effect of storage has been taken into consideration in box type solar cooker.as charging time is approximately 2-3 hours whereas the same heat takes a time of 4-5 hours for discharge, hence has a significant effect on performance of solar cooker the heat stored during charging can be used during night or cloudy days.

Conflict of interest

There are no conflicts to declare.

Acknowledgments

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ENERGETIC & EXERGETIC ANALYSIS OF A PARABOLIC TROUGH: CONCENTRATED SOLAR POWER PLANT

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Abstract
Solar energy is the most affordable source of energy. Parabolic trough systems are used to concentrate and extract heat, therefore it's very significant to analyse its performance in terms of energy and exergy. Exergy based analysis of the system ensures the eradication of losses, resulting in the yield of energy of the highest quality. In this paper, an investigation has been carried out using numerical simulation with an objective of analysis of Parabolic Trough Collectors on the basis of energy and exergy. Detailed second law analysis has been performed by varying the system and operating parameters through computer simulation. Exergy output has been determined by analysing the effect of major system parameters, namely, mirror reflectivity, glass transmissivity, absorptivity, the diameter of glass envelop, and the receiver. The operating parameters considered in the investigation are insolation and temperature rise parameters. The extensive investigation of the parabolic trough of a concentrated solar power plant for various design parameters in the range of operating parameters reveals that it is beneficial to operate the system at higher temperature as opposed to the preference of the operating system at lower temperature from purely thermal considerations.

Keyword
solar energy, exergy, thermal efficiency, heat gain, heat losses, parabolic trough, collectors

Introduction
Efforts had been made by many researchers to further improve solar power generation technology. Numerical simulation is performed for a power plant of 30 MW PT-SEGS. The analysis resulted in revealing that the variation of steam and heat transfer fluid (HTF) optimum temperature at different insolation. Solar radiation has a significant influence on the range of optimum temperature [1]. Kalogirous et al. [2] and Zarza et al. [3] investigate the PTC systems used for the generation of steam. The studies revealed that for steam generation, 48.6% of the insolation impending on the parabolic trough collector was utilized and the rest were losses, which were dissipated to the environment in various forms. The major losses were collection losses approximated to be 41%, and thermal losses were near about 7%. Prabhu [4] simulated and compared the Organic Rankine cycle parabolic trough with the steam Rankine cycle. The outcome indicated that at the average summer temperature, the steam Rankine cycle was much efficient and performed 15–25% better than the ORC. Zhiyong Wu et al. [5] simulated the receiver temperature, which was performed with the help of MCRT (multi-core run time) and fluent software. The solar radiation absorbed, properties of HTF and optical properties of the receiver are the parameters considered. D. Canavarro et al. [6] investigate optical model of the large parabolic trough. The radius of the evacuated tube was 70 mm, which resulted in a considerable increase in concentration, even without changing the acceptance angle of the optic. The new solutions represented a potential reduction in the field costs or even in O&M. Siqueira et al. [7] evaluated the thermal performance of the concentrator with the help of simulation software varying the parameters of the concentrator. The simulation program proved to be a powerful design tool for determining the thermal efficiency, thermal losses, and optical loss. Guzman et al. [8] calculated the solar radiation potential of Barranquilla, Colombia by simulation with system advisor model. The direct and beam radiation data is fetched from NASA-SSE. The energy storage system is incorporated in analysis and optimum size minimization methods is followed for Levelized Cost of Energy (LCOE) sensitivity analysis.

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Messai et al. [9] studied parabolic trough solar power plants in different Algerian places for analyzing the usable electricity and an economic study and suggested a solution to minimize the Levelized cost of electricity. Pidaparthi and Prasad [10], demonstrated the development and installation of a solar thermal parabolic trough field of 3 MW with the help of Abengoa as shown in Fig 6. The first one of its kind parabolic trough power plant in India was erected with the HTF used as Therminol VP-1 having a temperature range of 285 - 673 Kelvin. Controllers were installed in the plant to track the sun's real-time position for optimizing the energy absorption with no release of CO_2 into the atmosphere. The total covered area is approx. 8000 m^2 with and the total length of the collector is 1500 meters. Mustapha et.al [11] used mathematical analysis on various elements of the parabolic trough integrated on solar thermal power plant. Such a model was the theoretical transcription of the first principle of the thermodynamics applied to each part of the collector. Premjit et al. [12] numerically studied the parabolic trough receiver with an outer vacuum shell's performance, whereas Munoz et al. [13] present solar linear thermal collectors with thermal regime. Various simulation models have been developed through Engineering Equation Solvers (EES) and are validated Markus Eck, Tobias Hirsch [14], Fadar et al [15], Garcia et al. [16], Tsai and Lin [17] simulated different kinds of reflectors of a PTC collector using solid works to obtain the optimum thermal efficiency. Gupta and Kaushik [18] proposed an idea of direct steam generation solar power plant; different components of PTC were analyzed for energy and exergy performance. The maximum energy loss resulted in the condenser whereas the exergy loss was minimum in the collector. Aljundi [19] analyzed the Al-Hossien power plant in Jordan on the basis of energy and exergy factor and the outcome revealed maximum exergy destruction in the boiler (77%), followed by turbine (13%). Reddy et al. [20] perform energy and exergy analysis of components for different thermal power plants. Bespalko et al. [21] compared technologies for heat storage that can be utilized for unstable solar heat sources. The study reveals, sensible heat storage being the most appropriate for concentrated solar thermal power plant.

Methods

Parabolic trough model

The present study deals with the energetic optimization of parabolic trough collector. A wide range of insolation in the range of 500 to 1000 W/m^2 is considered depending on the location where the plant will be operated. Various studies reported the analysis of components of PTC that yielded the maximum thermal efficiency. The thermal and energetic performance of the parabolic trough depends upon several systems and operating parameters. System parameters can be categorized into the fixed and variable parameters.

Fixed parameters (Table 1) do not substantially influence the thermal and energetic performance. Variable parameters (Table 2) are proposed for investigation and the range of parameters has been selected based on the literature related to the design of the parabolic trough of CSPP. Table 3 shows the range of operating parameters.

Table 1. Fixed Parameters

S. No.	*Description*	*Parameter*	*Value*
1	Width of module (m)	W	5.76
2	Length of module (m)	Lc	12.27
3	Mirror Length (m)	L	11.9
4	Intercept factor	IF	0.92
5	Emissivity of Glass Cover	ϵ_c	0.90
6	Outer glass Diameter (m)	D_{co}	0.115
7	Inner Glass Diameter (m)	D_{ci}	0.109
8	Outer absorber Diameter	D_o	0.070

Table 2. Variable Parameters

S. No.	*Description*	*Parameter*	*Value*
1	Mirror reflectivity	ρ	0.72-0.92
2	Transmissivity-absorptivity product	$\tau\alpha$	0.74-0.94
3	Inner absorber Diameter	D_i	0.045-0.065

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Table 3. Operational Parameters

S. No.	*Description*	*Parameter*	*Value*
1	Insolation (W/m^2)	I	500-1000
2	Temperature difference between inlet & oulet.(K)	ΔT	50-200

The total solar power input to the collector system of the parabolic trough is Q_I, which is calculated as

(1) $$Q_I = I \times A_a \times N_c \times N_r \times N_m$$

(2) $$A_a = (W - D_{co})L$$

Where, *W=width of the module, D_{co}=Glass absorber outer Diameter, L=Length of the trough, I =Total insolation*. Out of total power input, the amount of power captivated by the parabolic trough collector; Q_a

(3) $$Q_a = I_b A_a N_c N_\gamma N_m \rho \tau_g \alpha_a (IF)$$

Calculation of losses and temperature is carried out through the iteration process. Heat transfer from the glass envelop occurs by convection and radiation:

(4) $$Q'_{c-s} = \pi D_{co} L h_{w(air)} (T_{co} - T_a) + \pi \varepsilon_c D_{co} L \sigma (T_{co}^4 - T_s^4)$$

Where, Convective Heat transfer coefficient h_w (air), can be calculated by McAdams correlation.

(5) $$\frac{h_w D_{co}}{k_{air}} = 0.04 + 0.54\left(\frac{\rho_{air} V_w D_{co}}{\mu_{air}}\right)^{0.52}$$
For $0.1 < Re < 1000$
$$\frac{h_w D_{co}}{k_{air}} = 0.3\left(\frac{\rho_{air} V_w D_{co}}{\mu_{air}}\right)^{0.6}$$
For $1000 < Re < 50000$

Useful Heat Gain (Qu) of the absorber/receiver is calculated as.

(6) $$Q_u = [(\rho \tau \alpha) \times (\pi D_{co} L) \times I_b] - Q'_{c-s}$$

Calculating receiver tube temperature:

(7) $$T_r = T_{fm} + \frac{Q_u}{\pi D_i h_f}$$

The value of mass flow rate & heat transfer coefficient of the fluid is considered in the succeeding set of equations.

(8) $$m_f = \frac{Q_u}{\Delta T \times C_p}$$

(9) $$\mathrm{Re} = \frac{4 \times m_f}{\pi \times D_i \times \mu}$$

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(10)
$$\Pr = \frac{\mu \times Cp}{K_f}$$

(11)
$$If\ \mathrm{Re} < 2300$$
$$Nu = 3.66 + \frac{0.668\,\mathrm{Re} \times \Pr \times D_i}{1 + (0.04 \times \mathrm{Re} \times \Pr \times D_i)^{0.23}}$$

(12)
$$If\ \mathrm{Re} > 2300$$
$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\Pr^{(1/3)}$$

Heat transfer coefficient is given as

(13)
$$h_f = \frac{Nu \times K_f}{D_i}$$

The inner glass cover temperature is calculated as

(14)
$$T_{ci} = \left(\frac{Q_{l(c-a)} \times \ln \frac{D_{co}}{D_{ci}}}{2\pi K_c L} \right) + T_{co}$$

Heat loss from the receiver to the glass envelop is considered through radiation, which is calculated as.

(15)
$$Q'_{r-c} = \frac{\pi D_o \sigma (T_r^4 - T_{ci}^4)}{\left[\frac{1}{\varepsilon_r} + \frac{D_o}{D_{ci}} \left(\frac{1}{\varepsilon_c} - 1 \right) \right]}$$

The iteration process is to be accomplished by linking the heat transfer equations. If the values are found to be equal in Equation 4 and equation 14, additional procedures are followed. If both values are unequal, another slightly higher value of T_{co} is supposed to be assumed and further, the iteration steps are repeated to obtain the results.
The overall heat loss coefficient is determined by

(16)
$$U_l = \frac{Q_{loss}}{\pi \times D_i \times L(T_r - T_a)}$$

Further collector heat removal factor (F_r) is found by

(17)
$$F_r = \frac{mC_p}{U_l A_r} 1 - e^{\left[\frac{U_l A_r F'}{mC_p} \right]}$$

The Collector efficiency factor (F'), the ratio of useful gained energy to the energy collected is determined by [22]

(18)
$$F' = \frac{1/U_l}{\frac{1}{U_l} + \frac{D_o}{Dih_f} + \frac{D_o}{2K_r} \ln \frac{D_o}{D_i}}$$

`

Useful heat gain by the thermic fluid is calculated as

(19) $$Q_{uu} = F_r[Q_a - U_l A_r (T_i - T_a)]$$

The thermal collector efficiency (η_{th}) is defined as the useful energy gain (Q_{uu}) to the incident solar energy over a specific period and is calculated as

(20) $$\eta_{th} = \frac{Q_{uu}}{Q_I}$$

Pressure loss ΔPf of the thermic fluid through the receiver tube is calculated by friction factor (f) and velocity of thermic fluid.

(21) $$\begin{gathered} If\ \mathrm{Re} < 2300 \\ f = {}^{16}\!/_{\mathrm{Re}} \end{gathered}$$

(22) $$\begin{gathered} If\ \mathrm{Re} > 2300 \\ f = 0.0791 \times (\mathrm{Re})^{-0.25} \end{gathered}$$

(23) $$V_f = \frac{m_f}{\frac{\pi}{4} Di^2 \rho_f}$$

Exergy destruction in the receiver tube is due to pressure drop, which adds up to the pumping power to make the fluid flow through the tube.

(24) $$E_{desp} = m_f \times T_{am.} \frac{\Delta p_f}{\rho_{fm} \times T_{fm}}$$

The exergy destruction because of heat loss from the receiver tube is calculated as

(25) $$E_{desu} = m_f \times C_p \times T_{am} \times \ln\left[\frac{T_{out}}{T_{in}}\right]$$

The useful exergy is determined by

(26) $$E_u = Q_u - E_{desp} - E_{desu}$$

The exergy flow of the incoming solar irradiation (E_s) is considered through the Petela model, according to the succeeding equation [22].

(27) $$E_s = Q_s\left[1 - \frac{4}{3}\left(\frac{T_{am}}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{am}}{T_{sun}}\right)^4\right]$$

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The exergetic efficiency (η_{ex}) is defined as the fraction of useful exergy output to the exergy flow of sun.

(28)
$$\eta_{ex} = \frac{E_u}{E_s}$$

Results and discussion

The analysis of the parabolic trough of the solar collector is carried out using the performance parameters, namely, overall loss coefficient, useful heat gain, thermal, and energetic efficiency, have been evaluated as a function of major system design parameters, namely, mirror reflectivity, the diameter of the fluid, carrier tube, transmissivity-absorptivity product; and major operating parameters, namely isolation and temperature rise parameter. The performance parameters value is displayed in figures with the temperature rise parameter, to bring out its effect on various performance parameters. The value of the selected parameter varies in each figure, while the other parameters have a set of fixed values.

For instance, Figure 1 shows the effect of reflectivity of the mirror on the useful heat gain, where it can be seen that with an increase in reflectivity of the mirror from 0.72 to 0.92, the magnitude of the useful heat gain enhances, this is because as the mirror reflectivity increase, large amount of energy is reflected by the absorber tube, hence an increase in useful heat gain is observed.

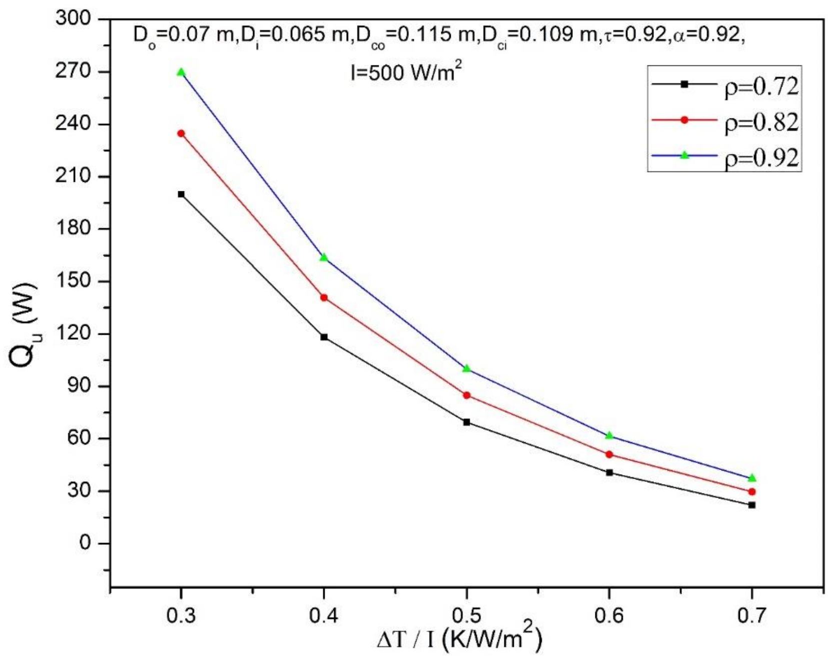

Fig. 1. Effect of variation of mirror reflectivity on useful heat gain

Figure 2 shows the effect of reflectivity of mirror glass on the useful heat gain and thermal efficiency. It can be seen that with the decrease in mirror reflectivity, the loss decreases, which increases the useful heat gain. This is responsible for increase in the thermal efficiency. Even though the effect of reflectivity is very small for bringing change in the thermal efficiency, for different temperature rise parameter values. As the value of the temperature rise parameter is increased, the thermal efficiency comes down, it is well known that when ΔT is very low, the absorber cover temperature is minimum. This lower temperature leads to the small amount of heat loss to the environment, thus resulting in the highest thermal efficiency.

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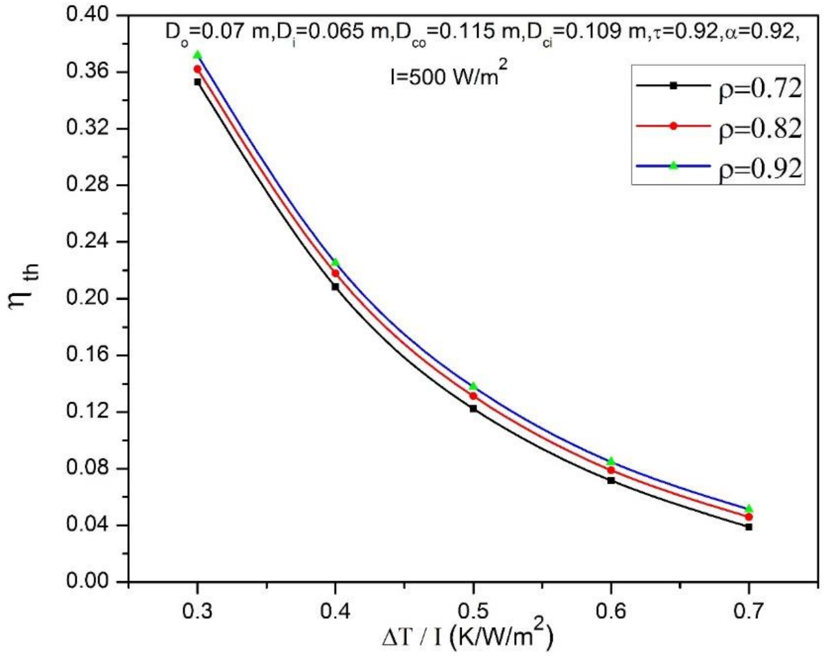

Fig. 2. Effect of variation of mirror reflectivity on thermal efficiency

Figure 3 shows the effect of mirror reflectivity on exergetic efficiency. It is seen that with rise in the temperature rise parameter, a significant enhancement in the energetic efficiency is observed. However, beyond the temperature rise parameter value of 0.3, the energetic efficiency decreases. To absorb high thermal energy at a low value of temperature rise, the flow rate of HTF is very high, which results in a large amount of friction loss. Hence, the combination of high friction loss and a low amount of thermal gain results in a very low value of energetic efficiency. Whereas at high value of temperature rise parameter (<0.3), the temperature of the fluid is very high resulting in heat loss and vis-a-vis exergy destruction and hence the sudden decline of energetic efficiency4df.

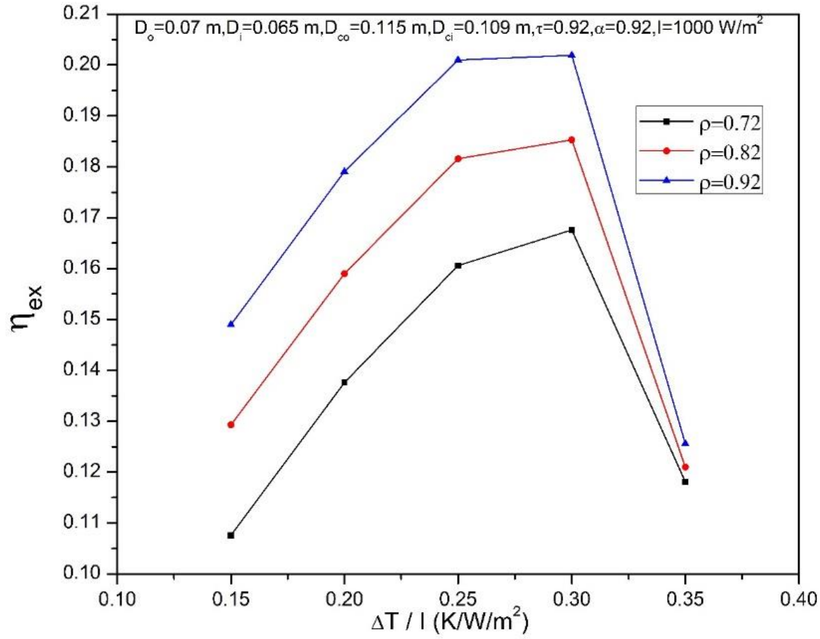

Fig. 3. Effect of variation of mirror reflectivity on exergetic efficiency

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Figures 4 & 5 shows the effect of different effective transmittance products on the thermal efficiency for fixed values of other parameters corresponding to the insolation values of 500 W/m^2 and 1000 W/m^2 respectively. It is seen that a higher value of τα results in a slightly higher efficiency, although the effect is more visible in the case of a lower insolation value. At a fixed value of ΔT/I = 0.5, and increasing the τα from 0.74 to 0.94, an increase in thermal efficiency of 12% to 17% is observed. This represents a substantial change as a result of the changing products of transmittance absorptance. An increase in this product results in a higher amount of insolation being ultimately absorbed, leading to higher thermal gain.

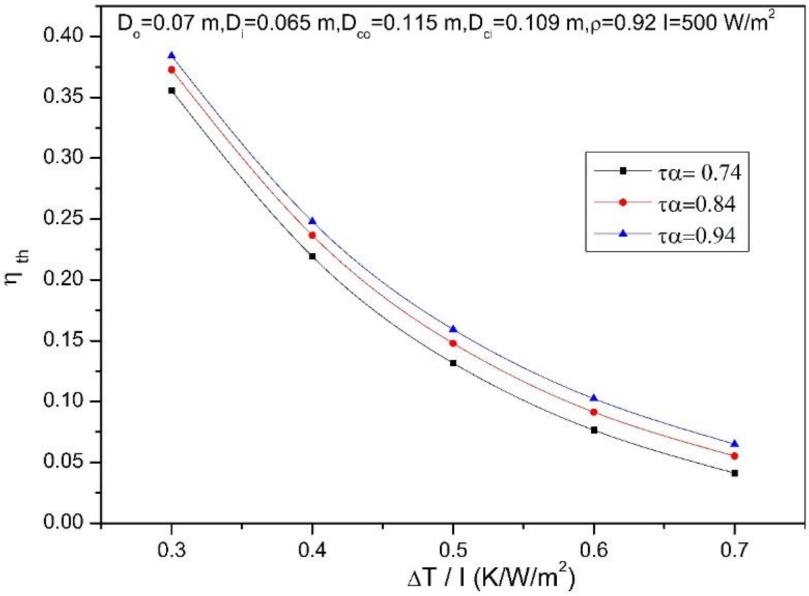

Fig. 4. Effect of variation of transmissivity and absorptivity on thermal efficiency at I = 500 W/m^2

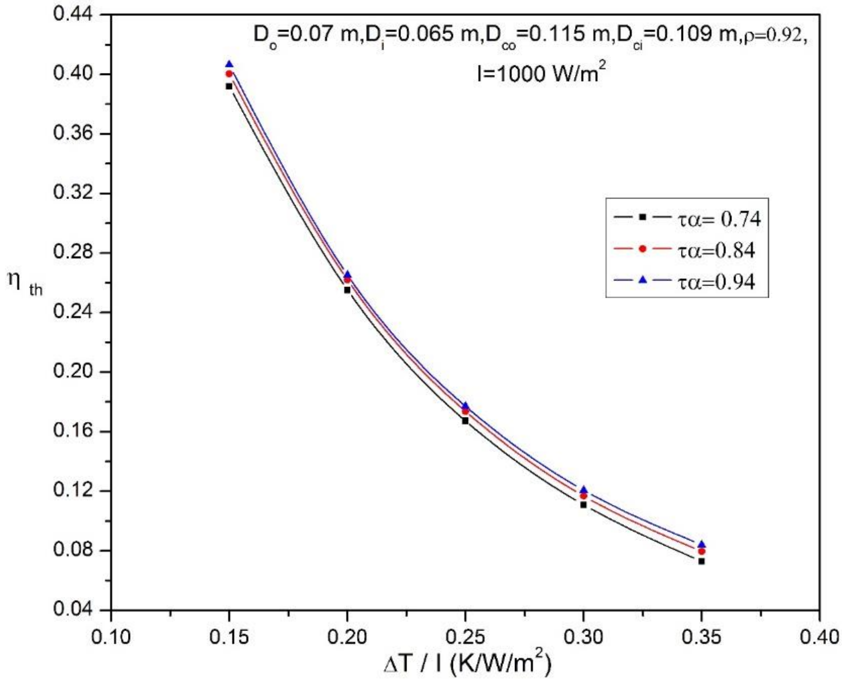

Fig. 5. Effect of variation of Transmissivity and absorptivity on thermal efficiency at I = 1000 W/m^2

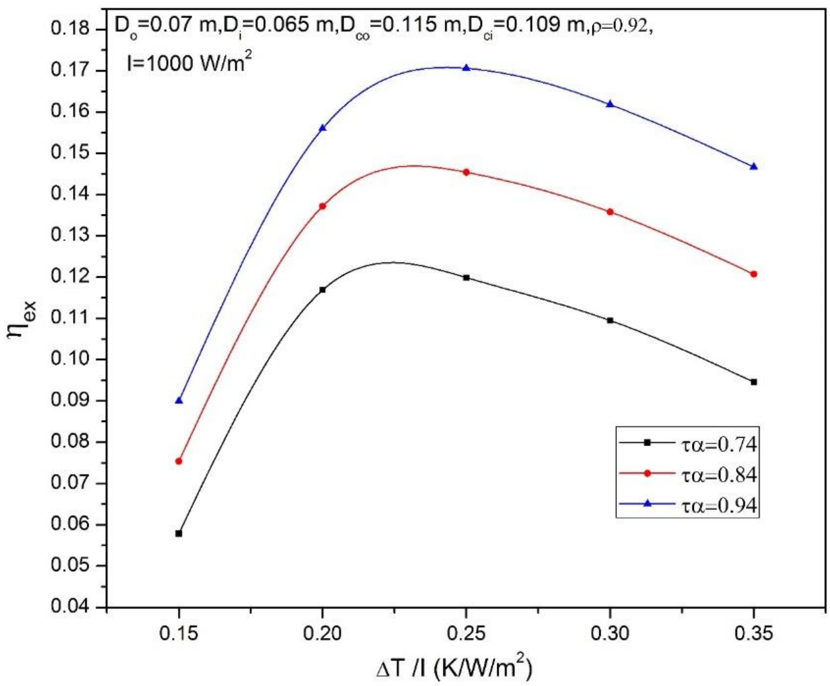

Fig. 6. Effect of variation of transmissivity and absorptivity on exergetic efficiency

The effect of effective transmittance–absorptance product on energetic efficiency has been depicted in the Figure 6. It is noteworthy that the exergetic efficiency is very strongly affected by the variation of τα. The figure reveals that at lower temperature rise parameter value, the results of performance of system does not vary too much for change in the transmittance absorptance product. Whereas this variation is wider at higher magnitude of temperature rise parameter. Higher exergetic efficiencies with an increase in transmittance – absorptance products show that a better quality of energy is obtained.

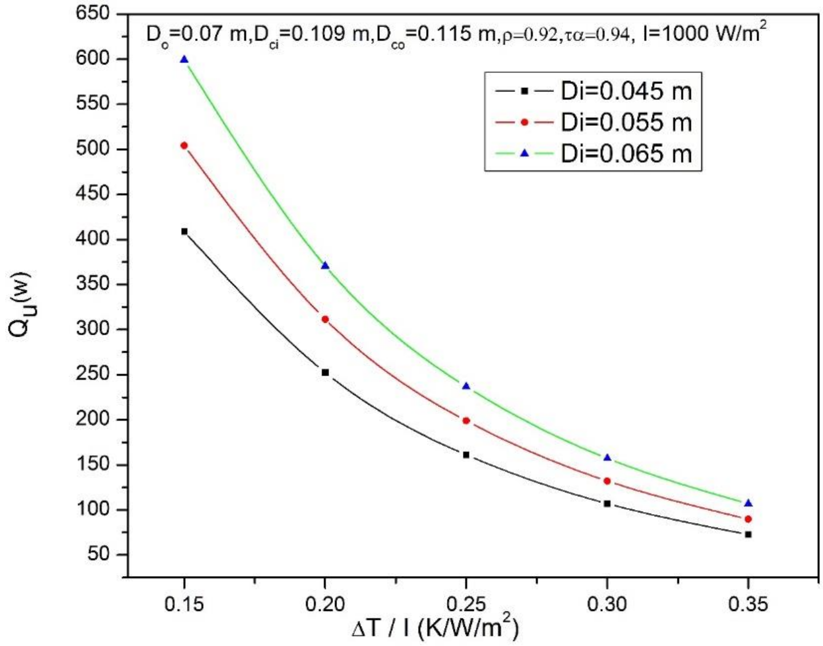

Fig. 7. Effect of variation of receiver tube diameter on useful heat gain of fluid

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The effect of diameter on performance parameters can be seen in Figs. 7 and 8. It is seen that a larger diameter results in a slightly higher value of useful heat gain, thermal and exergetic efficiencies. Although the effect seems to minimize at a higher value of temperature rise parameter.

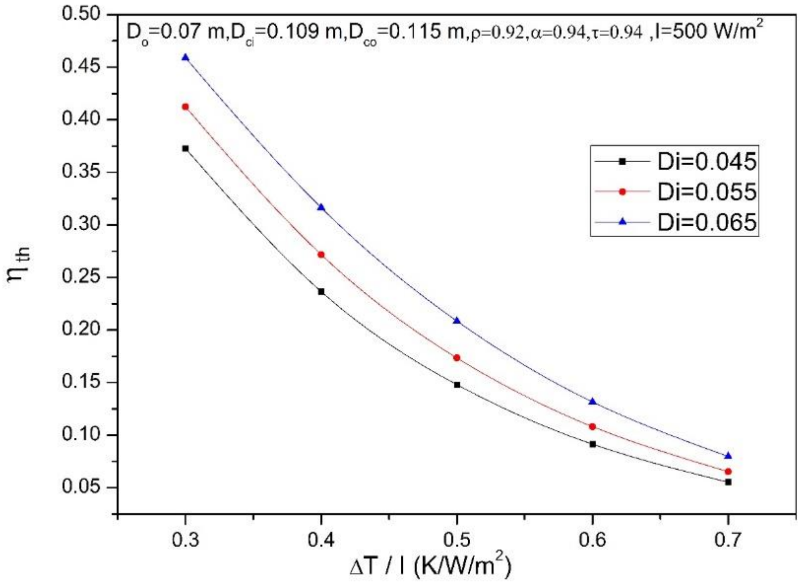

Fig. 8. Effect of variation of receiver tube diameter on thermal efficiency

Fig. 9 shows the effect of diameter on exergetic efficiency, it is noteworthy that the exergetic efficiency values are strongly affected by the values of the temperature rise parameter. For the minimum value of temperature rise parameter and smaller receiver inner diameter, a high rate of fluid flow is seen, which resulted in the higher friction loss in the system observed. This low exergy gain and high amount of friction loss results in a negative value of exergetic efficiency; hence at a lower value of temperature rise parameter, the low diameter of the receiver tube becomes unacceptable.

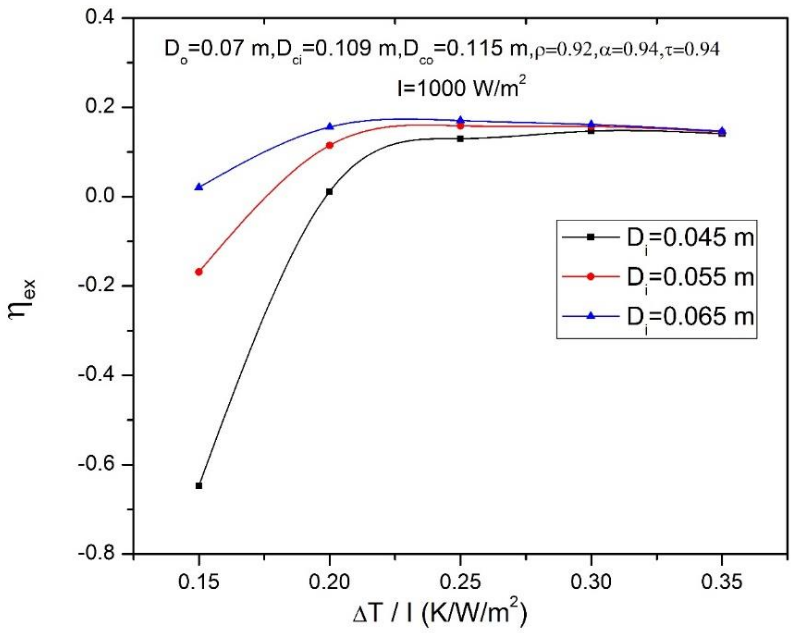

Fig. 9. Effect of variation of receiver tube diameter on exergetic efficiency

Impact

The present analysis of parabolic trough concentrated solar power plant deals with the energy and exergy component of the system. The analysis is carried out to fetch the best suited set of parameters that are prolific for enhancing the performance of the parabolic trough concentrated solar power plant. The present analysis will have an impact on determining the working condition of the power plant on the basis of fluid temperature. This analysis will lead to the development of renewable source for power generation as well as will also take care of the environmental aspect, which is damaged by other fuels used in power plants operations.

Conclusions

The CSP Parabolic Trough analysis by simulation technique carried out to investigate the effect of dominant design parameters in a power plant viz. transmittance-absorptance product, mirror reflectivity, receiver tube diameter. The designed system is analysed based on the thermal and exergetic performance. It is seen that performance of the trough is low as the ΔT magnitude increases. The exergetic efficiency seems to get better by increase in ΔT. The results revealed that the operating the system at higher temperatures is prolific as compared to lower temperature. Following are the major conclusions:

- The transmittance-absorptance product has a negligible effect on the thermal efficiency of the system, whereas the exergetic efficiency is seen to improve with increasing value of τα. Better exergetic performance resulting from higher transmittance product shows that a better quality of energy is obtained.
- A higher value of reflectivity for better thermal and exergetic efficiency is recommended.

Although the benefit of using a larger receiver tube with a larger diameter is not visible for a higher value of temperature rise parameter, for the low value of temperature rise, it is not recommended to use a smaller receiver tube with a small diameter.

Conflict of interest

There are no conflicts to declare.

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STRATEGIC RESPONSES IN CORPORATE TAX PLANNING USING OPPORTUNITY AREAS

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Abstract
Using sampling for companies from EU member states and Ukraine, we find a significant and positive relationship between the company size and the amount of corporate taxes. We use questionnaires to determine the role of corporations in expanding the scope of tax management and discover an increased effect of corporate planning. Moreover, we offer a model of corporate tax planning considering the opportunity areas. This model determines the taxation framework for a company. We have developed a map to determine the degree of effective tax planning for a company. Finally, we use the functional-activity model of the tax planning process to substantiate the conclusion that the responsibility of the participants in such a process stipulates good business reputation. In general, our results suggest that corporate tax planning is an effective way to optimize tax liabilities.

Keywords
tax planning, tax policy, taxation, zones of opportunity, development strategy, corporate responsibility

Introduction

The substantive characteristics of such concepts as 'development', 'profitability', and 'taxation', their ontological basis, subordination and interrelation with other concepts of the productive continuum determine the features of corporate management and tax planning to develop algorithms for the upward movement of companies. Tax relations are formed between the state and taxpayers and are at the intersection of public interests of the state and private interests of taxpayers. They are an integral part of social responsibility. Thus, the state is interested in replenishing the relevant budget, while taxpayers focus on reducing deductions from their income. Is there a conflict of interest? Definitely. Tax policy is formed at the state level. The European Union's policy on direct taxes is aimed at providing a level playing field for companies to ensure healthy competition and create a favourable tax environment. In general, EU countries seek to standardize tax rates and oblige companies to pay taxes exactly where they make a profit. According to analytical data and statistical observations, the standard VAT rate fluctuates in European countries. Thus, in Switzerland it equals 7.7%, whereas in Germany the standard VAT rate is 19%. Estonia and France account for 20% while the Czech Republic, Lithuania, and Latvia have the VAT rate as high as 21%. In Poland and Hungary it comes to 22% and 27% correspondingly. The income tax rate in Hungary is 9% while Switzerland has 8.5% (federal tax rate) plus a cantonal tax. In Germany it accounts for 15%, whereas in Poland and the Czech Republic the income tax rate comprises 19%. In Slovakia this figure is as high as 22%. What is more, the tax base is different in the countries. The list of countries by tax rate is shown in Fig. 1.

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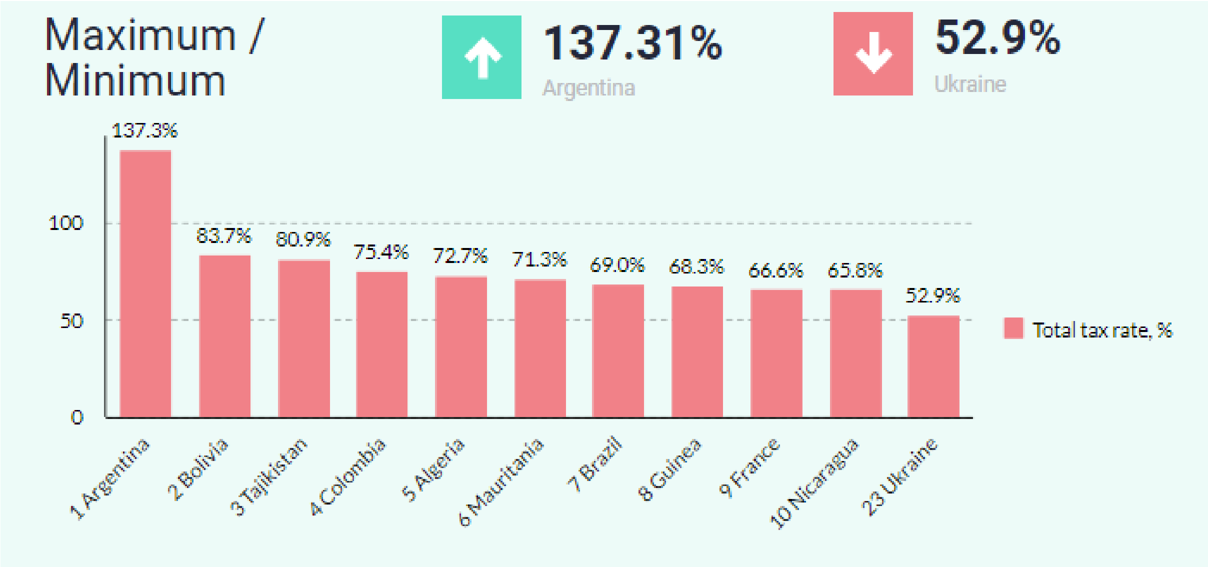


Fig. 1. Country Ranking: The Highest Tax Rates (by the Total Tax Rate). *Source: Compilation based on [1]*

One of the EU criteria that determine the need to pay income taxes are the degree of economic relations between the potential taxpayer and the state. For 2021, the European Commission has approved an agreement of finance ministers of the world's seven most industrialized economies on the introduction of income tax rate on large corporations of at least 15%. According to EU statistics, this will increase annual revenues to its budget by 50 billion euros [2].

Taxes have a significant impact on the financial and economic activities of companies. Therefore, the scientific discussion takes place at the intersection of tax planning, financial management, accounting, corporate governance and corporate social responsibility. Thus, researchers [3] conclude that trade-off, hierarchy and theories of free cash flow play an important role in explaining the monetary determinants of companies, influencing the strategy of tax planning and corporate management. In this aspect, draw your attention to the research results on corporate financial indicators as well as their impact on corporate governance and calculation of tax payments [4]. Depending on the scale and financial capabilities, scientists [5] recommend using different models of tax management — from the simplest, which are reduced to tax accounting or tax planning, to complex ones that cover the full range of tax management tools such as tax planning, tax analysis, monitoring of business transactions, tax accounting and reporting, and tax control. A number of instruments such as analytical, normative, statistical ones and a balance sheet are defined as legitimate (by Suchman [6]) just as special methods of tax planning, i.e. methods based on tax benefits and alternative tax solutions are. The emergence of numerous innovative technologies on the market, including financial and monetary technologies and new products causes a need to regulate the taxation system at all levels [7].

Previous studies discovered a relationship between the values of financial indicators and the reporting system of companies [8]. Due to different approaches to reporting, some of its articles change, which is the reason for achieving different values of financial indicators [9]. This has an impact on the amount of taxes. When linking tax planning and financial indicators, there is a negative impact of tax planning on liabilities [10,11]. Therefore, the management of companies resort to different methods of optimizing tax liabilities, including illegitimate tools, i.e. tax evasion or tax avoidance, and legitimate methods such as tax planning [12].

Domestic stakeholders are interested in conducting tax planning in companies due to the impact on the company's reputation as a social [13], and economic [14] phenomenon. At the same time, researchers [14] note the importance of the information and its impact on the practice of tax planning. However, domestic stakeholders sometimes have an adverse response to tax planning due to the expected significant operating costs [15]. Studies by Landolf and Hartnett on tax planning in the corporate governance system are of scientific and practical interest [16,17]. In implementing tax planning Landolf identifies the following benefits for corporations: business planning of tax payments, formation of tax calendars, submission of tax reporting, objective choice of methods and tools for tax optimization. Feller & Schanz complement the body of knowledge by providing empirical evidence of the impact tax planning has on the assessment of corporate social responsibility. In this case, other stakeholders (tax authorities) can obtain information on the potential risks of tax planning of the corporation through activities in the field of corporate social responsibility [18].

Academic research in the field of corporate tax planning is expanding along with the growing public interest. In addition, increased scientific attention to the issue of corporate tax planning in connection with strategic development was facilitated by the processes of globalization and internationalization which raised the problem of integration of national tax systems into the world economy. The results of the study [19] confirm the importance of strategic interaction with business partners; and the impact of such interaction on the amount of tax liabilities is important.

Tax regulation still varies from country to country, including the European Union, although countries aim for a policy of general harmonization. Thus, in Ukraine, the highest state body has the right to impose taxes whereas in Switzerland taxes are set by cantons (regions) regardless of the highest authority. Led by the desire for European integration, Ukraine has reduced the number of taxes. This reduction is not a cut-down or abolition of certain types of taxes but their certain combination. That is, the results of such a decision do not change the burden on taxpayers. In Poland, in 2020, personal income tax was calculated at a rate of 18-32%, while income up to PLN 8,000 was not taxed. In Switzerland, the federal tax rate was up to 11.5% plus a cantonal tax, with the 12.20% effective personal income tax rate in the canton of Geneva for the income of CHF 6,000 per month and 26.15% for the income of CHF 20,000 per month. Tax rates in EU member states for legal entities are as follows. In 2020, the value added tax rate in Switzerland was 7.7%, however, it comprised 2.5% for basic necessities and 3.7% for the hotel business. Banking service, insurance premiums, residential real estate, educational and medical services regulated by the casino are not taxed. The value added tax rate in Poland was 23%, with 0% for exports to countries outside the EU; 5% for books, magazines, basic foodstuffs; 8% for pharmaceutical products and passenger traffic. Financial, insurance and educational services were not taxed. Also, the legislation of the countries provides for various tax benefits if companies will operate in areas approved by public authorities [2].

When studying the concept of corporate taxes, Jacob [20] identifies the real effects of corporate taxation and they have a significant impact on the income and profits of companies. The scientist concludes there is a consensus that higher corporate tax rates reduce corporate investment, foreign direct investment, aggregate growth and innovation.

The concept of tax planning is developed in the direction of corporate social responsibility. Elgood et al. [21] consider this direction when determining the unique tasks of tax departments. Such tasks include creation, protection and optimization of value; management of tax risks associated with doing business; ensuring compliance with tax laws and reporting requirements. The authors conclude that tax planning should focus on optimizing financial results and tax risks, both in relation to strategic agreements and current operations.

The work of Rashid et al. [22] aimed at establishing a link between financial performance and the level of tax expenditures in the model of internal tax planning. Using the method of integrated regression model, OLS can act as a special method of tax planning of the company.

In his doctoral project Princen [23] developed the theory of corporate planning through the influence of taxation on corporate financial decision-making. This approach is justified in the study through tax optimization. The author argues that the use of tax planning strategies has a significant impact on financial and investment decisions of the company.

Scientific and practical interest in corporate tax planning in recent years is also explained by the fact that the general public awareness of corporate tax activity is increasing. At the same time, increased efficiency of crisis management of companies during the COVID-19 pandemic is coupled with the effectiveness of financial and accounting instruments in relation to taxes [24]. In our opinion, the relevance of further research on this problem is due to its multifaceted nature. And it is also coupled with the fact that as a process tax planning is influenced by many economic and social factors and governed by macro- and macro-level factors. In our opinion, tax planning is a kind of tool that allows you to choose the most effective way of tax activities of the company and create directions for its development strategy.

This article contains new ideas on corporate tax planning. The strategic consequences of its implementation in corporations will also be discussed regarding the actions on preventing violations of public interest when outlining the boundaries of tax planning. Areas of opportunity are also defined by the participants of tax planning in the corporation and through the scope of their corporate responsibility.

The purpose of this article is to develop an innovative approach to corporate tax planning considering areas of opportunity. Recognition of its locus in the corporate tax management system and implementation will optimize the taxation system, maximize the income and profits of companies and increase financial stability.

Methods

The corporation as an organisational and legal form of management expands the scope of tax management and responsibility for forecasting tax expenditures and control over their payment. At the same time, a well-established tax planning process can have a significant impact on a company's success both economically and socially. The current study attempts to analyse tax planning in its general context, i.e. without dividing actions into tax evasion and avoidance.

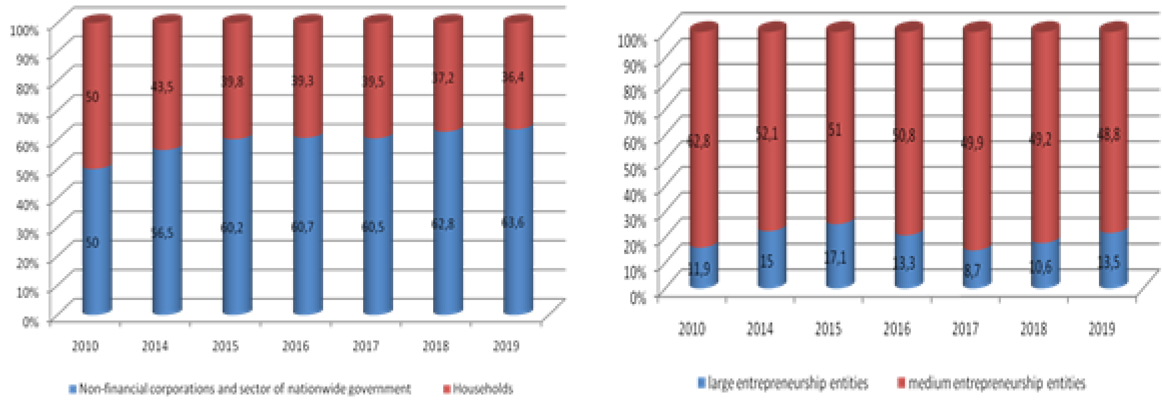
The sample for this study is represented by agricultural corporations in Ukraine. The research period is the effect of Legislative Acts of Ukraine regarding taxation in 2019-2020. Data for branch analyses are retrieved from the statistics collected and disseminated by the State Statistics Service of Ukraine. We use statistical methods to grade agribusiness corporations in Ukraine in terms of their revenue and to assess the dynamics of output and its distribution among companies operating in the sector of Ukrainian agriculture. The study carries out an interview to determine the main advantages of corporate organisation of economic activity in the opinion of middle and senior managers. Number of respondents, N = 45 people from 20 companies, including 31 middle and 14 senior managers. We used the method of legislative review to establish the tax rate in the agricultural sector. The assessment of statistical data was carried out to group taxes by structure and amounts paid by Ukrainian agricultural enterprises to the budget (for the period of the first half of 2019). A model of corporate tax planning has been developed and presented using infographics. The successive stages are singled out and completed with tools and methods. We present the model implementation on the example of four Ukrainian agribusiness companies. In this study analytical methods are used in the course of developing a taxation framework of an agricultural company regarding tax types, tax base, and tax rates. We control that the framework will be determined separately for each company, so we present a general section. The map for determining the degree of effective tax planning in the corporation was developed and presented in this study as a questionnaire. Emphasis is placed on the importance of the organizational component in the process of tax planning. Based on organisational modelling, the scheme of participants in the tax planning system in the corporation and the scope of their corporate responsibility are presented.

Results and discussion

<u>Corporation as a structural element of the national economy: features of functioning and specifics of taxation</u>

The development of the national economy greatly depends on large enterprises (corporations), which occupy leading positions in manufacturing and sale of products and are developers of modern technologies, investors, etc. This is confirmed by statistics from many countries: the lion's share in the structure of national gross domestic product belongs to large corporations [25]. In general, increasing the number of corporations in Ukraine and in agriculture in particular is an important economic mechanism that creates new strategic goals of foreign economic policy, means and conditions for Ukraine's participation in the international division of labour and attracting foreign direct investment into the national economy.

The corporate sector of the Ukrainian economy is represented by joint stock companies, integrated formations, and non-joint-stock corporate sector [26]. The development of corporate relations in the Ukrainian agricultural sector is of particular importance as this industry receives significant flows of investment, including foreign one. Let us turn to statistics. In 2019, the 20 most profitable companies together received UAH 162 billion in net profit. This comprises 71% of the total profit received by the 200 largest Ukrainian companies in Ukraine in 2019. As for the agro-industrial complex, the 20 most profitable companies include the Myronivsky Khlibo product corporation with a profit of UAH 5 billion in 2019 [27,28]. The dynamics of output volume and its distribution among companies operating in the Ukrainian agricultural sector is shown in Fig. 2.



a) Output in Agriculture, percentage to total

b) Turnover of business entities by Agriculture, in % to the total of business entities

Fig. 2. The dynamics of output volume and its distribution among companies operating in the Ukrainian agricultural sector. *Source: own study based on* [27].

In the first half of 2019 companies in agriculture, forestry and fisheries paid taxes in the amount of UAH 21 billion 232 million 365.5 thousand (Table 1). In the first half of 2019, the agricultural sector ranks 11th in terms of the taxes paid. APK-Invest PJSC became the leader among agricultural enterprises [28].

Table 1. The structure and amount of taxes paid by agribusiness companies to the budget for the first half of 2019. *Source: own systematizy based on* [28].

Structure and amount of taxes, thousand UAH							
PIT and military tax	Income tax	Rent	Excise tax on goods produced in Ukraine	VAT on goods produced in Ukraine	Property tax	Ecotax	Single tax
7571974.5	542436.4	642216.2	2473.4	8259366.8	2163171.0	41779.0	1793302.6

Agricultural companies, like other entities, are looking for ways to optimize the tax burden. One of them is the introduction of tax planning which is an important element of the company's tax management system. Tax management aims to build the most optimal relations between the company and the state in the matter of tax calculation and payment. It is important to note that savings due to optimization of taxes and payments increase the entity's own financial resources. Therefore, the achievement of the main goals of entrepreneurial activity is ensured by increasing the level of income, financial stability and growing profitability.

This confirms the significant and positive relationship between the company size and the amount of taxes and a wide range of corporate opportunities for business organization through modelling inter-company relations. Given the cognitive potential, we conducted a survey of top and middle managers in the Ukrainian agricultural sector (number of companies, n = 20). This provided an opportunity to model the main advantages of corporate organisation of economic activity based on the managers' opinion (the number of respondents is 45, including 31 middle and 14 senior managers).

The following factors are defined as advantages:

- ability to raise funds through the issuance of shares, which allows the accumulation of funds of a significant number of investors (62% of the senior managers and 23% of the middle managers);

- facilitation of business activity management through greater regulation in the definition of responsibilities and powers and distribution of the control function between the governing bodies (72% of the senior managers and 44% of middle managers);

- opportunities for stakeholder rotation and flexibility in terms of dynamic investment proposal (38% of the senior managers and 13% of the middle managers);

- risk reduction due to the principle of limited liability (68% of the senior managers and 39% of the middle managers);

- others (23% of the senior managers and 14% of the middle managers).

Among the main negative consequences of tax rules for agricultural companies noted by the respondents are potential excessive tax regulation, high risk of double taxation, frequent changes in tax legislation and a significant tax burden. In this aspect, we note that the agricultural sector is sensitive not only to the level of taxes, but also to their combination. As of 2020, the tax legislation of Ukraine gives alternatives for agricultural companies in terms of the taxation system [29].

Tax planning as a tool to improve business profitability: Analytical aspect

In this study, corporate tax planning is understood as a purposeful activity that involves assessing and making management decisions to justify and choose the option of paying taxes, which will optimize the tax system and maximize the income and profits of companies. We base this definition on an activity approach that allows us to outline the process of organizing tax planning in a corporation. The corporate tax planning model combines several stages and involves certain steps for its implementation (Fig. 3).

At the Preparatory Stage, the national taxation system, tax rates and amounts of tax payments are monitored. The dynamics of the company's activity (income from the main activity and related activities; the amount of costs from operating and other activities) is estimated. The tax burden is analysed. The taxation framework is assessed. Tax planning specialists analyse all the statutory benefits for each tax, which are applied to the company with respect to the activity size and type, and develop a detailed plan for the use of benefits for individual taxes, as well as analyse possible tax risks.

At the Analytical Stage, alternative tax activities are assessed. This is when we suggest compiling a table in the form that is designed to characterize the taxation framework of the entity. We also propose to form typical business transactions that will be implemented by the business entity. Indicator-markers are set on the basis of analytical plans for the volume of activity, level of profitability, and marginal tax burden. Achieving such indicators is the subject of taxation and other types of control (production control, financial control, etc.). At this stage, the entity's tax calendar is compiled for the current period taking into account tax liabilities, tax payment deadlines and tax reporting. This plan must be consistent with the entity's overall financial plan. For the purpose of further tax control, the scale of deviations of the corresponding indicators-markers is developed.

The Organisational Stage characterizes the assessment of tax accounting and reporting (determination of the tax base, calculation of taxes and payments, accounting and tax records, preparation and submission of tax reports) and determination of the tax burden level. It deals with the control over compliance with tax legislation and accounting policies, assessment of the tax plan implementation. Proper implementation and effectiveness of tax planning in the company depends on its organizational support. One of the factors of the efficient Organizational Stage of the offered functional model for corporate tax planning is the control carried out at the level of employees of Accounting and Finance Department. Such control involves assessing accuracy of accounting for taxable objects and calculations of individual taxes and fees, work on tax returns, timeliness of their payment and submission of tax returns to avoid penalties. In this aspect, it is important that the registration of actual business transactions must comply with applicable law. In our opinion, an important specialist in the organisational structure of corporations is a tax planning specialist who works in the Accounting and/or Finance Department. Such a specialist has the competence and knowledge of the national tax system, features and timing of paying taxes to the budget, fees and contributions to extra-budgetary funds, and the ability to make tax calculations and declarations.

Every company has its individual approaches to tax planning since they are determined by the scale of activity, industry, type of activity, areas of opportunity. However, we propose a general model of tax planning, which combines several stages and involves certain steps for implementation. The model considers the principle of business continuity and focuses on the formation of the tax field to minimize the tax base for individual taxes or payments. Every company sets the tasks of tax planning and solves them using the ways that do not violate an applicable law.

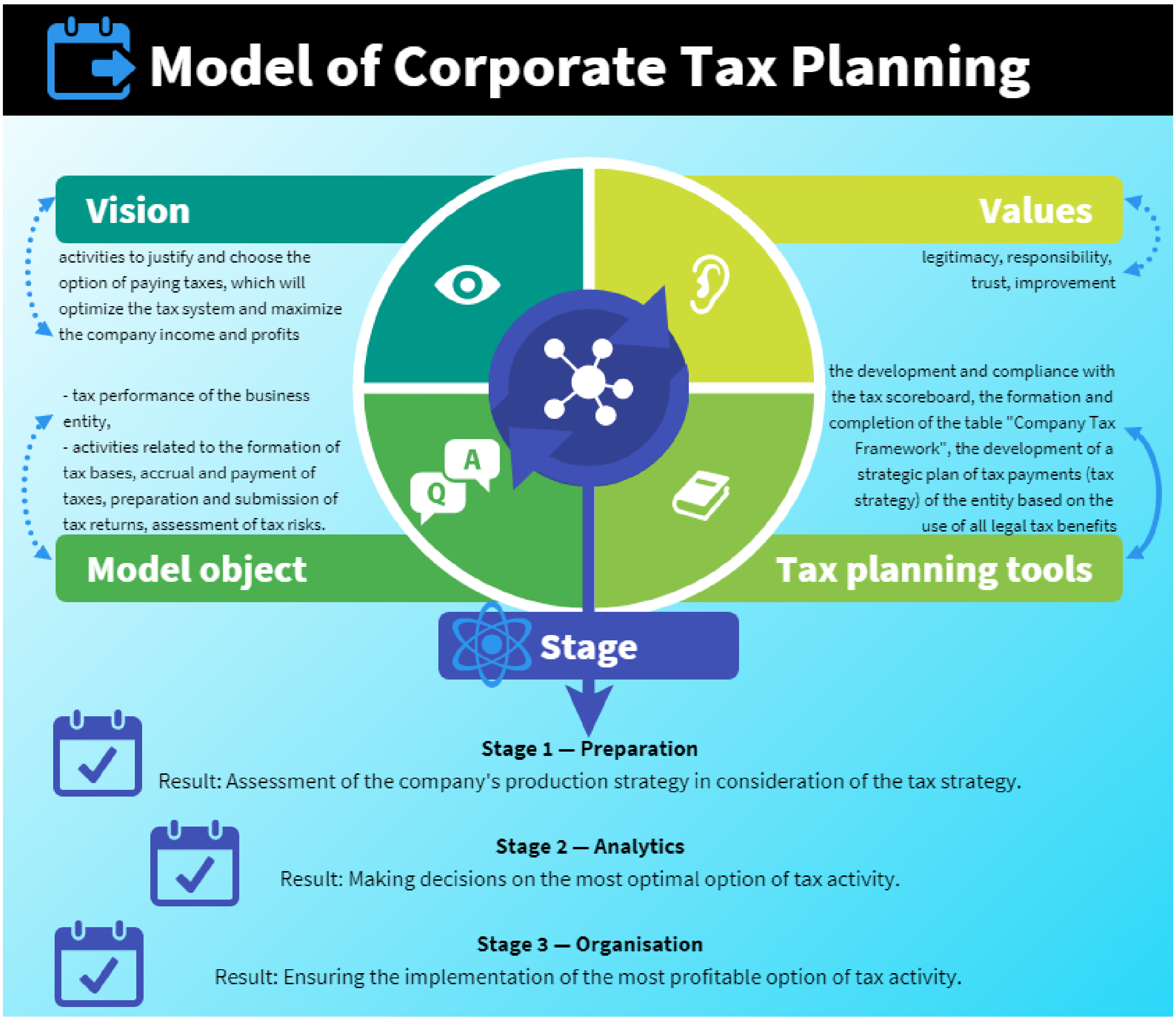


Fig. 3. Innovative model of corporate tax planning. *Source: developed by the author*

Implementation of the corporate tax planning model

Tax planning is a highly precise and creative process. Accuracy is that the calculation of taxes depends on the level of income, profit, and, therefore, on the level of expenditures. On the other hand, only with the right approach is tax planning a tool for legally saving assets for further business development.

The developed model of corporate tax planning (Fig. 5) is implemented on the example of companies operating in Ukrainian agribusiness. For this purpose, we have chosen Novaagro Trading House LLC, Crocus Agro LLC, Agroin agrogroup, and KVADRO group. Companies were studied for the conditions of the national tax system, tax rates and amounts of tax payments. The national taxation system, tax rates and amounts of tax payments were monitored. An assessment was provided for the dynamics of the company's activities and the scale of the taxation framework, which means the set of taxes and fees that the taxpayer is required by law to pay. Based on the results, we have developed a taxation framework for these companies. In this study, the assessment of the taxation framework means a set of taxes and fees that the taxpayer is required by law to pay. The general section of the form of the taxation framework is shown in Table 2.

The Analytical Stage deals with an assessment of alternative tax activities. At this stage, we suggest compiling a table in the form that is designed to characterize the taxation framework of the entity. We also propose to form typical business transactions that will be implemented by the business entity. Indicator-markers are set on the basis of analytical plans for the volume of activity, level of profitability, and marginal tax burden.

Table 2. Taxation framework of an agricultural company considering opportunity areas (general section).
Source: developed by the author

<table>
<tr><th>Type of tax and fee</th><th>Tax base</th><th>Tax rate</th><th colspan="2">Notes</th></tr>
<tr><td>A. Income tax</td><td>Monetary expression of the object of taxation</td><td>18%</td><td colspan="2">Privileges under separate taxation systems</td></tr>
<tr><td>B. Value-added tax (VAT)</td><td>is determined by the contract value, taking into account national taxes and fees</td><td>20%</td><td colspan="2">Payers of the third group have the right to decide independently on the VAT payment. VAT exemption in case of choosing the single tax rate of 5%.</td></tr>
<tr><td>C...</td><td>...</td><td>...</td><td colspan="2">Availability of benefits under certain tax systems, tax exemption, choice of tax rate, etc.</td></tr>
<tr><th colspan="5">Calculations and analytical data on the company</th></tr>
<tr><th colspan="2">Monetary assessment, thousand UAH</th><th>Previous year</th><th>Current year</th><th>Changes</th></tr>
<tr><td colspan="2">Amount of accrued taxes and fees</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Amount of taxes and fees paid</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Tax arrears</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Penalties for late payment of taxes and fees</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Level of tax burden on the enterprise for the reporting year,%</td><td></td><td></td><td></td></tr>
</table>

Achieving such indicators is the subject of tax and other types of control (control of production, finance, etc.). At this stage, the company prepares a tax scoreboard for the current period, taking into account tax liabilities, tax payment deadlines and tax reporting. This plan must be consistent with the entity's overall financial plan. For the purpose of further tax control the scale of deviations of the corresponding indicators-markers is developed. Further, we propose general actions to optimize the tax activities of agricultural companies (Tab. 3).

Table 3. General actions to optimize the business tax activities, considering opportunity areas.
Source: developed by the author

Proposed measures	Actions taken	Notes
Transition to a special annual period for farmers	Submission of income tax return for the first half of the year	No mark in Field 9 Special marks of the Declaration of affiliation to agricultural production
Avoidance of the simplified taxation system in connection with the transition to the payment of other taxes and fees.	Application for the transition no later than 10 calendar days before the beginning of a new calendar quarter (year) and sending a tax letter stating the election of a special tax period by the agricultural enterprise.	Increasing the size of the regulatory monetary valuation of agricultural land and single tax rates is the reason that other tax systems are more profitable from an economic point of view.
Adjustment of the financial result downwards using inventory charts for accounting, storage of seeds and finished products	Development of accounting policies for financial and tax accounting	- improvement of accounting policy for accounting and tax purposes; - assessment of tax risks (possible penalties): implementation of the most rational — from a tax point of view — placement of assets and profits of the organization
Development of an effective system of internal control of tax risk management	Establishment of a corporate internal tax control service	Development or improvement of corporate standards and changes in the organizational structure as needed

The organisational stage characterizes the assessment of tax accounting and reporting (determination of the tax base, calculation of taxes and payments, accounting and tax records, preparation and submission of tax reports) and determination of the tax burden level. Control over compliance with tax legislation, control over compliance with accounting policies, assessment of the implementation of the tax plan. We have developed and proposed a map to determine the degree of effective tax planning in the corporation (Table 4).

Table 4. The map to determine the degree of effective tax planning in the corporation concerning opportunity areas. *Source: developed by the author*

Questions	Answer options	Score
1. Does your company have a position of tax management / tax planning specialist?	Yes No Functions are performed by another specialist	3 1 2
2. Does the company have an internal audit service?	Yes No Functions are performed by another service	3 1 2
3. Are there different terms of the agreements that consider tax, contractual and economic consequences?	Yes No Partially (for some indicators)	3 1 2
4. Does your company use general planning and budgeting?	Yes No Partially (for some indicators)	3 1 2
5. Does the company deal with annual tax planning of its activities with respect to changes in national tax legislation?	Yes No Partially (for some indicators)	3 1 2
6. Is tax accounting enshrined in the accounting policies?	Yes No Partially (for some indicators)	3 1 2
7. Are there different accounting methods that form the valuation of assets, the procedure for recognizing sales revenue and write-off that are directly related to the taxation of the company and its financial condition?	Yes No Partially (for some indicators)	3 1 2
8. Does the company meet the deadlines for taxes and fees to the budget and payments to extra-budgetary funds?	Yes No Partially (for some indicators/payments)	3 1 2
9. Does the company implement the most rational — from a tax point of view — placement of assets and profits of the organization?	Yes No Partially (for some indicators)	3 1 2
10. Does the entity exercise the primary control over legal provisions in the course of calculation and payment of taxes and fees and accounting policies by using certain techniques in tax accounting?	Yes No Partially (for some indicators)	3 1 2
11. Is the implementation of the planned performance indicators monitored?	Yes No	2 1
12. Are targets being adjusted for internal or external business conditions?	Yes No	2 1
13. Are profit targets calculated with respect to the company tax burden?	Yes No	2 1
14. Are profit targets calculated with respect to the company development strategy?	Yes No	2 1
15. Is the use of the company's cash in tax flows being estimated?	Yes No	2 1

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In Table 5 we show the key designed to calculate the scores that evaluate the indicators to determine the degree of effective tax planning in the corporation considering opportunity areas

Table 5. The key for calculating the scores that evaluate the indicators to determine the degree of effective tax planning in the corporation considering opportunity areas. *Source: systematized by the author*

Group of indicators	Question number	Range	Multiplier	Minimum score	Maximum score
I Organisational	1-5	1-3	0.3	1	3
II Methodological	6-10	1-3	0.4	1	3
III Analytical	11-15	1-2	0.3	1	2
Total score, x				5	13.5

The score for each group of indicators (I-III) is calculated by multiplying the amount by points per factor. 2) The total score is obtained by summing the indicator for each group. Evaluation of results: number of points $10 < x \geq 13.5$ — sufficient level; $7 < x \geq 10$ — satisfactory; $5 \geq x \geq 7$ — low.

Next, the tax burden is calculated using the company's profit and according to the formula:

$$PNpr = PnP : Pr \times 100\ \% \quad (1)$$

where PNpr — tax burden on an individual business through the company's profit rate, %;
PnP - the total amount of taxes and fees paid in the reporting year;
Pr — profit in the reporting year, thousand UAH.

Results on the degree of effective tax planning in the corporation are presented in Table 6.

Table 6. Matrix of results on the degree of effective tax planning in the corporation.
Source: summarized by the author

Company	Degree of effective tax planning in the corporation (max. 13.5)	Assessment of the tax burden level, PNpr	The need for tax planning in the enterprise
Novaagro Trading House LLC	9 (sufficient)	28%	There is a need for tax planning and opportunities
Crocus Agro LLC	8 (satisfactory)	42%	Tax planning is a priority in the company. After all, the level of tax burden is significant and can negatively affect business activity
Agrain Agrigroup	7 (insufficient)	43%	
KVADRO Group	7 (insufficient)	45%	

We also propose a scheme that reflects the participants of the tax planning system in the corporation and can be the basis for changes in the business organizational structure, corporate documents and job descriptions of those responsible (Fig. 4).

To ensure the implementation of the scheme (Fig. 4) tax planning is considered as part of the management of financial and economic activities in the company within a single strategy of economic development. In this aspect, the tax planning process will ensure the systematic use of legitimate and optimal tax methods and techniques in conditions of limited resources, the possibility of their alternative use and opportunity areas. Analytical activities and reporting of a tax planning specialist are the basis for evaluating the company's activities to develop a business plan.

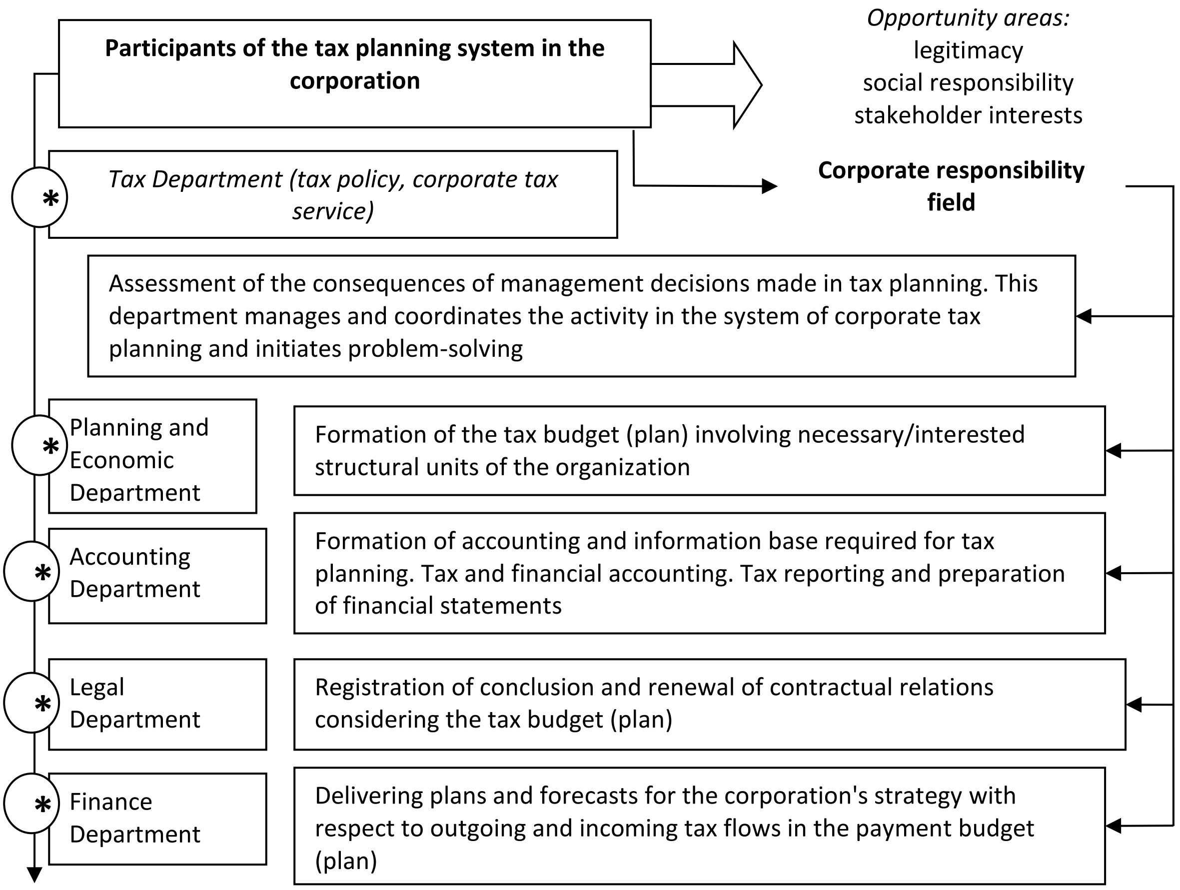

Fig. 4. Participants of the tax planning system in the corporation, the scope of their corporate responsibility considering opportunity areas. *Source: developed by the author*

Impact

Tax planning is a component of the strategic management of corporations, which affects the economy, increasing the company's profitability, as well as reputation through improving corporate social responsibility in the strategic perspective. The developed innovative model of tax planning is offered to the company management so that they can determine the locus of tax planning in corporate management to legally optimize tax expenditures for further business development. The implementation of such a model can be completed by both comments on changes in taxation and on their basis recommendations to the relevant departments of the enterprise, and corrective action on deviations that have arisen.

Our research shows that overly aggressive tax minimization can lead to significant adverse outcomes such as fines as well as reputational damage. Therefore, tax planning is a way to optimize tax expenditures. To do this, the company's management must support the tone at the top, which balances the goal of increasing revenue and the need for tax expenditures. Contributing to an appropriate level of thinking, management plays a key role in shaping the company's appetite for profits and ensuring decision-making on strategic tax planning.

After implementing the proposed scientific and practical development, the economic effect is expected through the preservation of working capital; increase in the overall efficiency of economic activity; growth financial stability. However, we note that the results of tax planning should be assessed not only by the amounts of reduced taxes and benefits, but also in terms of reducing possible losses and expenses that would be inevitable in business without considering the existing features of taxation.

Implementation of the tax planning model at Novaagro Trading House LLC will provide an opportunity to reduce the level of tax burden by 1.5%. When implementing the model in such companies as LLC Crocus Agro, AgrogroupAgroin, and Group KVADRO, the level of their tax burden will be reduced by 1.4%; 1.6%; 2.5% respectively. To do this, we built a tax field, conducted tests of contractual relationships of the enterprise, and proposed the use of optimal forms of contracts in forecasting and determining taxable income and performance indicators to minimize the tax base for individual taxes or payments. It should also be noted that the implementation of the model of corporate tax planning involves the availability of qualified personnel who can ensure its step-by-step implementation as well as understands the scope of personal responsibility.

Since tax planning initiatives can assess both risks and benefits it should be seen as a proxy for business reputation and social responsibility.
The expected social effect from the implementation of the proposed scientific and practical development will have a positive impact on the social sphere by preventing the violation of public interest. At the same time, tax planning should consider labour and civil law which are directly related to tax optimization schemes.

What is more, the impact of tax planning on the economic and social efficiency of the corporation should be assessed on the basis of systematic and structured accounting, analytical and tax information. Given this, we consider it appropriate to form an annual taxation framework for a company and assess the level of tax burden.

Conclusions
Corporate tax planning activities are at the intersection of economics, finance, and management within the opportunity areas such as legitimacy, social responsibility, and interests of stakeholders. In recent years, there has been an increase in public awareness of corporate tax activities.

The novelty of this study includes organizational and methodological tools of tax planning, considering the opportunity areas which rest upon causal links between changes in the legislative framework, internal and external business environments. Such development is proposed in the context of continuous improvement of the corporation's management system, which is possible by expanding the competencies of employees who are responsible for tax planning. The set of tax planning tools has been improved through the taxation framework for a company considering the opportunity areas. This allows for further effective tax activities in the corporation in respect of changes in legislation, social responsibility and the interests of stakeholders.

Tax planning has been studied as a legitimate tool of tax management, which aims at optimizing tax payments to improve business performance. We concluded that in modern conditions, tax planning should be carried out constantly, regardless of the level of tax burden. However, according to the results of the survey, most respondents found the main advantage of the corporation, and that is problem-solving facilitation in terms of activity management. This means that tax planning can be effective through the effective organization of company activities. The proposed measures for the tax planning considering the opportunity areas can bring real value in financial terms. This is possible because when taxes are fully understood and expected, the corporation's management will be able to regain control over cash flows, debt payments and other liabilities.

The results of this study are relevant to improving the tax performance of corporations. This approach should be based on consistent consideration of factors, criteria and principles of conservation of corporate resources, targeted improvement of employee competencies and introduction of tax planning tools to optimize tax payments.

Conflict of interest
There are no conflicts to declare.

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SUSTAINABILITY ASSESSMENT OF DIFFERENT NANOPARTICLE FOR HEAT EXCHANGER APPLICATIONS: AN INTUITIONISTIC FUZZY COMBINATIVE DISTANCE-BASED ASSESSMENT METHOD

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Abstract
The rate at which the conventional energy sources are depleting is a matter of concern, and there have been major attention on this to make the thermal systems environment friendly, efficient, economic, sustainable, technically reliable. Sustainability of five different types of nanoparticles (Ceramic, carbon based, metal based, polymeric, and lipid based) from the perspective of four aspects involving cost, efficiency, technicality and environmental effect, in heat exchangers has been assessed. The analysis is carried out using the intuitionistic fuzzy combative distance-based assessment ($IFCODAS$) method. In order to measure the sustainability of nanoparticles, a set of eleven evaluating criteria have been accredited on the basis of expert opinions and focus group meetings. By amalgamating the intuitionistic fuzzy set (IFS) theory as well as the use of distance-based assessment ($CODAS$) method, the $IFCODAS$ method has permitted the decision-makers to rate the alternative five nanoparticles pertaining to each criterion. On the basis of the results obtained from $IFCODAS$ method, it is observed that the carbon-based nanoparticles have an immense potential to provide significantly reliable and sustainable thermal system than other nanoparticles.

Keywords
heat transfer, nanoparticles, intuitionistic fuzzy set

Introduction
Every facet of life involves the usage of heat energy in certain forms and as per a definition, the amount of energy which is transferred between two substances at a different temperature is called heat [1,2]. The flow of energy occurs from the substance which is at a higher temperature to the substance which is at a lower temperature. Conduction, convection and radiation are the three basic mechanisms by which the heat transfer takes place [3,4] . Additionally, the heat transfer fluids' future lies in the nanofluids in several heat transfer applications, pertaining to the fact that they have been found to possess boosted thermo-physical properties which render them potentially expedient in voluminous applications in heat transfer. Various types of nanoparticles viz. metals (Cu, Ag, Au), carbon

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nanotubes, oxide ceramics (Al_2O_3, CuO), carbide ceramics (SiC, TiC) and number of liquid like oil, ethylene glycol and water are examined [5,6].

Akbari et al. [7] numerically studied the thermal behaviour of turbulent and laminar flow of water/ Al_2O_3 nanofluid having a volume fraction of $\varphi = 0\text{–}4\%$ of solid nanoparticles in Reynolds numbers in a range of 500 to 25000. The results reveals that for turbulent flow, the use of solid nanoparticles in higher volume fractions have a progresses heat transfer as compared to the laminar flow., Azmi, et al. [8]. Elamsa-ard Kiatkittipong [9] has investigated the heat transfer coefficients of SiO_2/water and TiO_2/water nanofluid up to 3% volume concentration flowing in a circular tube. It has been deduced from the investigation that the heat transfer enhancement gets inversely increased with twist ratio. The SiO_2/water nanofluid with a volume concentration of 3.0% delivers a heat transfer coefficient of 27.9% higher than water flow for the same twist ratio of five. Nonetheless, the value of heat transfer coefficient of TiO_2/water nanofluid evaluated at the same concentration has been found to be 11.4% greater than water for twist ratio of five. Chougule and Sahu [10] studied the Al_2O_3/water and CNT/water nanofluids in a heat exchanger tube inserted with helical twisted tape and reported that CNT/water delivers higher thermal characteristics.

Eiamsa-ard and Wongcharee [11] analysed the thermal characteristics by integrated nanofluids with dual twisted-tapes in a micro-fin tube and reported that the selected idea delivers higher thermal performance factor. (Magesh Babu et al. [12], Hosseinnezhad et al. [13], Jafaryar et al. [14] reported that average Nu increases as the twist ratio decreases, because the counter-swirl flow twisted-tape along with increase in volume fraction of Al_2O_3 nanoparticles in the base fluid. Mohammadiun et al. [15] have conducted an experimental study on Al_2O_3/ethylene glycol (EG) nanofluid turbulent flow through corrugated quipped with twisted tapes although Naik et al. [16] experimentally a plain tube and tube with twisted tape for thermal analysis purpose with water/propylene glycol based CuO nanofluids and reported higher performance using the inserts in the tube.

Kumar et al. [17] determined the thermohydraulic behaviour of Fe_3O_4/water nanofluids inside a double pipe U-bend and the result revealed there is enhancement of Nu by 38.75%. Liu et al. [18]have surveyed the effect of algae on the combined toxicity of nano- $TiO_2$and lead (Pb), while Deng et al. [19] have scrutinized the effects of Zn-doped TiO_2 nanoparticles and it has been explored that increasing the amount of Zn doping in the TiO_2 film, the performance of the cell decreases, which has been ascribed to introducing a large number of ZnO clusters and producing more surface defects in the TiO_2 film that act as electron-hole recombination centres.

In the recent past, the main consideration has been fixated on the usage of nanoparticles in the arena of structural nano ceramics, wear resistant coatings and functional nanomaterials for optoelectronics, photonics and bio-imaging D'Amato et al. [20]. have addressed the progress of doped and pure TiO_2NPs for applications in photocatalysis and DSSC electrodes fabrication Vollath et al. [21] fetched the potentials of synthesizing ceramic nanoparticles in a microwave plasma. Matsumoto et al. [22] have synthesized SiN-based ceramic nanoparticles by the crosslinking and pyrolysis of the micelles. Such sort of ceramic particles are anticipated to be germane to catalysts, surface modification, and electric device preparation.

A model glucose biosensor has been developed by Shen et al. [23] using immobilization of glucose oxidase on the iridium-containing carbon working electrode's surface covalently by the usage of glutaraldehyde, and have signified its applicability for the progression of single usage, disposable electrochemical biosensors formulated on H_2O_2 detection with the usage of an oxidase. (Zhou et.al [24]; Ngoy et al. [25] and Zhang et al. [26] have grafted a long chain polymer along with a diamine in order to offer a large CO_2 anchoring site for the formation of carbamate, covering multi-walled carbon nanotubes (MWNTs) in order to augment the surface area as well as the pore volume. It has been undoubtedly established by these studies that the shape of carbon nano materials is correlated with their toxicity. He et al. [27] have proposed that NPs with slight negative charges and particle size of 150 nm were found to be more efficiently. These results could further serve as a guideline in the rational design of drug nano carriers with maximized therapeutic efficiency or worth.

This present work focused on developing a multi-criteria decision structure ($IFCODAS$) for assessment of sustainability using varying nanoparticle types in heat exchangers. This system integrates a fuzzy set based weighting method that inculcates the preference/views of the decision-makers in to get the dominance of evaluation criteria. The used numerical model determines the dominance of the system as well as the operating parameters in a selected range. The numerical model designed is used to determine the dominance of a nanofluid out of number of fluids used on the basis of different criterion viz. sustainability, environmental aspect, reliability, efficiency aspect, technical aspect, etc.

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Fuzzy and intuitionistic fuzzy set

Definition1. Fuzzy sets (FS) [28,29].

The set Z which is composed by x, and a fuzzy set $\tilde{a}$ which is defined by a membership function $\mu_{\tilde{a}}(x)$, measuring belonging of x to $\propto.\mu_{\tilde{a}}(x)$ signifies the membership of x in $\tilde{a}$,

(1) $$\alpha = \{(x, \mu_{\tilde{\tilde{a}}}(x)|x\epsilon Z\}$$

Definition2. Intuitionistic fuzzy set (IFS) [29]

If Z be the collection of objects x, and $\beta\epsilon Z$ be a fixed set, then intuitionistic fuzzy set β be defined as:

(2) $$\beta = \{(x\ , \mu_{\beta}(x), \vartheta_{\beta}(x))|x\epsilon Z$$

Where $\mu_{\beta}(x)$: Z→ $[0,1], x\epsilon Z \rightarrow \mu_{\beta}(x)\epsilon[0,1]$ represents the degree of membership of the member x∈Z to the set β, and $\vartheta_{\beta}(x): Z \rightarrow [0,1], x\epsilon Z \rightarrow \vartheta_{\beta}(x)\epsilon[0,1]$ is non-membership degree of the member x∈Z to the set β. μ_{β} and $\vartheta_{\beta}(x)$ generally placates $0 \leq \mu_{\beta}(x) + \vartheta_{\beta}(x) \leq 1, \forall$ x∈Z. In addition to membership and non-membership degree, an indeterminacy degree, called "hesitancy degree" purported of x to the set β, which is quite unalike the numbers $\mu_{\beta}(x)$ and $\vartheta_{\beta}(x)$ signifying the membership and non-membership degree of the member x∈Z to the set β, thus indeterminacy degree measure of x∈Z to the set β is defined as:

(3) $$\pi_{\beta}(x) = 1 - \mu_{\beta}(x) - \vartheta_{\beta}(x), x\epsilon X$$

Consequently, an intuitionistic fuzzy number β, customarily be denoted by $\beta = (\mu_{\beta,}\vartheta_{\beta}, \pi_{\beta})$ which encompassed the membership, non-membership as well as indeterminacy degree.

Definition3. Arithmetical operations [30].

Let $\gamma = (\mu_{\gamma}, \vartheta_{\gamma,}\pi_{\gamma,})$ and $\beta = (\mu_{\beta}, \vartheta_{\beta}, \pi_{\beta})$ are the β. The arithmetical operations amongst these two numbers can be depicted as:

Addition

(4) $$(\gamma\oplus\beta)=(\mu_{\gamma,}\vartheta_{\gamma}, \pi_{\gamma})\oplus(\mu_{\beta}, \vartheta_{\beta,}\pi_{\beta}) = (\mu_{\gamma} + \mu_{\beta-}\mu_{\gamma}\mu_{\beta,}\vartheta_{\gamma}\vartheta_{\beta,}1 + \mu_{\gamma}\mu_{\beta} - \mu_{\gamma} - \mu_{\gamma} - \vartheta_{\gamma}\vartheta_{\beta})$$

(5) $$\oplus_{j=1}^{n} \gamma_j = \oplus_{j=1}^{n} (\mu_{\gamma_j}, \vartheta_{\gamma_j}, \pi_{\gamma_j}) = (1-\prod_{j=1}^{n}\left(1 - \mu_{\gamma_j}\right), \prod_{j=1}^{n}\vartheta_{\gamma_j}, \prod_{j=1}^{n}\left(1 - \mu_{\gamma_j}\right) - \prod_{j=1}^{n}\vartheta_{\gamma_j})$$

Multiplication

(6) γ⊗β=(μ_γ,ϑ_γ,π_γ)⊗(μ_β,ϑ_β,π_β) =(μ_γ μ_β,ϑ_γ+ϑ_β-ϑ_γ ϑ_β,1+ϑ_γ ϑ_β-μ_γ μ_β-ϑ_γ-ϑ_β)

(7) $$\otimes_{j=1}^{n} \gamma_j = \otimes_{j=1}^{n} (\mu_{\gamma_j,}\vartheta_{\gamma_j}, \pi_{\gamma_j}) = (\prod_{j=1}^{n}\mu_{\mu_{\gamma_j}}, \prod_{j=1}^{n}(1 - \vartheta_{\gamma_j}), 1 - \prod_{j=1}^{n}\mu_{\gamma_j} - \prod_{j=1}^{n}(1 - \vartheta_{\gamma_j}))$$

(8) λ_γ=(1-(1-μ_γ)^λ 〖, 〖(ϑ_γ)〗 ^λ,(1-μ_γ)〗 ^λ- (〖ϑ_γ)〗 ^λ)

where λ called as crisp number.

Definition4. Geometrical distance [31].

The distance between intuitionistic fuzzy sets $\gamma = (\mu_{\gamma}, \vartheta_{\gamma}, \pi_{\gamma})$, and $\beta = (\mu_{\beta}, \vartheta_{\beta}, \pi_{\beta})$ is determined using Equation (9) and Equation (10).

The harmonic distance:

(9) $$d(\gamma, \beta) = \sum_{j=1}^{n}(|\mu_{\gamma}(x_j) - \mu_{\beta}(x_j)| + |\vartheta_{\gamma}(x_j) - \vartheta_{\beta}(x_j)| + |\pi_{\gamma}(x_j) - \pi_{\beta}(x_j)|)$$

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The Euclidean distance:

(10)
$$d(\gamma,\beta) = \sqrt{\sum_{j=1}^{n}\left(\mu_\gamma(x_j) - \mu_\beta(x_j)\right)^2 + \left(\vartheta_\gamma(x_j) - \vartheta_\beta(x_j)\right)^2 + \left(\pi_\beta(x_j) - \pi_\beta(x_j)\right)^2}$$

Definition5. Score (S_γ) and accuracy (H_γ) degree of the intuitionistic fuzzy set [32]
The score (S_γ) and accuracy $\left(H_\gamma\right)$ degree determined by using Equations (11) and (12), respectively.

(11)
$$S_\gamma = \mu_\gamma - \vartheta_\gamma$$

(12)
$$H_\gamma = \mu_\gamma + \vartheta_\gamma$$

Methodology
Present study espouses the methodology which consists of two parts. The first part is based on the criteria for sustainability assessments of five different types of nanoparticles, and the second part covered Intuitionistic fuzzy multi-criteria decision-making method ($IFMCDM$). These two parts are presented as follows:

Criteria for sustainability assessment of different types of nanoparticles
Based on the experts' views, literature review and focus group meetings, eleven indexes, related to four aspects involving cost (C), efficiency (E), technical (T) and environmental effect (EE) have been accredited as the evaluation criteria for sustainability assessment of different types of nanoparticles. Related to cost aspect these indexes are capital cost (C1), operating cost (C2) and durability cost (C3), whereas, with respect to efficiency aspect these indexes are thermal efficiency (E1), effective efficiency (E2) and exergetic efficiency (E3). In the point of view of the technical aspect, the indexes are technical complexity (T1) and technical reliability (T2), and for environment aspect the indexes finalized, are risk to ecosystem (EE1), wastage utilization (EE2), and toxic effect on environment (EE3). The criteria capital cost, operating cost, durability cost, technical complexity, risk to ecosystem and toxic effect on environment have been categorized as cost criteria (smaller the better) and rest have been categorized as benefit criteria (the larger the better).

Intuitionistic fuzzy multi-criteria decision making ($IFMCDM$):
A novel $MCDM$ is setup for sustainability ranking of different nanoparticles by combining the $IAHP$ and $IFCODAS$. The projected $MCDM$ method is shown in Fig.1. The $IAHP$ figure out the weightage of the sustainability assessment criteria for an energy storage technique facilitates. The Combinative Distance-based Assessment Method ($CODAS$) is used for rating intuitionistic fuzzy numbers for different nanoparticle.

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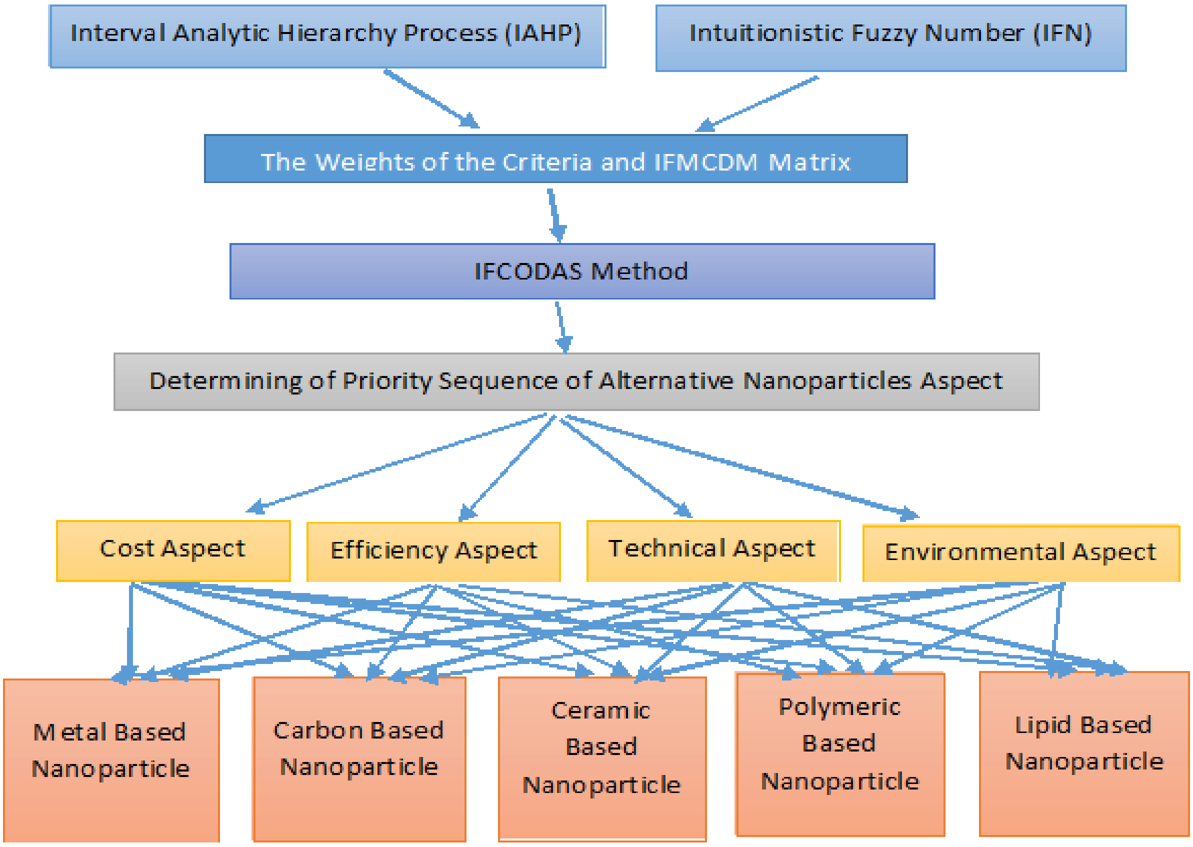

Fig. 1. The proposed MCDM method on IAHP and IFCODAS

Interval analytic hierarchy process (IAHP)

IAHP is made up of four steps [33]

STEP 1: Finding interval pair-wise comparison matrix.

Table 1 shows how to give fundamental scale of absolute number to different categories.

Table 1.The fundamental scale of absolute numbers

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	Intermediate value
3	Moderate importance	Knowledge and decision slightly favours one activity over another
4	Moderate plus	Intermediate value
5	Strong importance	Knowledge and decision strongly favours one activity over another
6	Strong plus	Intermediate value
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	Intermediate value
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation

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The administrators used a 9-scale system to set up the couplet juxtaposition matrix. Assuming that there are 'n' number of matrix $[M_1 \cdots \cdots M_n]$ which required to identify proportional weights. In an attempt to begin the pair wise comparison matrix, the conventional AHP technique has utilized the numbers from 1-9 often with their reciprocal for contrasting each doublet of factors. Occasionally, an individual number is unable to picturize the relative weight. For instance, there is no individual number which can depict the parallel priority of matrix to next one, while the administrator held the view that parallel importance of the matrix to next one lies between moderate and equal importance. So the interval number (1,3) can be employed to figure out the specific situation. The interval-comparison is calculated for 'n' matrix as suggested in literature [34].

(13)
$$Q^{\pm} = \begin{array}{c|cccc} & M_1 & M_2 & \cdots & M_n \\ M_1 & 1 & [q_{12}^L, q_{12}^U] & \cdots & [q_{1n}^L, q_{1n}^U] \\ M_2 & [q_{21}^L, q_{21}^U] & 1 & \cdots & [q_{2n}^L, q_{2n}^U] \\ & \vdots & \vdots & \ddots & \vdots \\ M_n & [q_{n1}^L, q_{n1}^U] & [q_{n2}^L, q_{n2}^U] & \cdots & 1 \end{array}$$

The relational significance of the j^{th} metric as compared to i^{th} metric is explored by following equation suggested by Saaty [34].

(14)
$$\frac{1}{[q_{ij}^L, q_{ij}^U]} = \left[\frac{1}{q_{ij}^U}, \frac{1}{q_{ij}^L}\right], i, j = 1,2, \ldots, n$$

Step 2: Decomposing the interval pair-wise comparison matrix [33].
The comparison of interval pair-wise matrix in equation (14) is split in two nonnegative matrices, as given in equations (15-16).

(15)
$$Q_L = \begin{bmatrix} 1 & \cdots & q_{1n}^L \\ \vdots & \ddots & \vdots \\ 1/q_{n1}^U & \cdots & 1 \end{bmatrix}$$

(16)
$$Q_U = \begin{bmatrix} 1 & \cdots & q_{1n}^U \\ \vdots & \ddots & \vdots \\ 1/q_{n1}^L & \cdots & 1 \end{bmatrix}$$

The finding of weightages for the matrices presented in equations (15-16) is carried out by the geometric mean method and the weight vectors computed are shown in equations (17-18), respectively.

(17)
$$W_L = [\omega_1^L \ \omega_2^L \ \ldots \omega_n^L]$$

(18)
$$W_U = [\omega_1^U \ \omega_2^U \ \ldots \omega_n^U]$$

STEP 3: Finding the interval weights [33].
For each matrix, interval weights are computed using Equations (19-21) as follows

(19)
$$s = \sqrt{\sum_{j=1}^{n} \frac{1}{\sum_{i=1}^{n} q_{ij}^{+}}}$$

(20)
$$t = \sqrt{\sum_{j=1}^{n} \frac{1}{\sum_{i=1}^{n} q_{ij}^{-}}}$$

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The weight vectors calculated using Equations (15-16) are represented by $\mathrm{W_L}$ and $\mathrm{W_U}$, respectively, whereas ω_j^L and ω_j^U are the weights of the j^{th} metric in $\mathrm{W_L}$ and $\mathrm{W_U}$, respectively,

(21)
$$\omega_j^{\pm} = [k\omega_j^L \; m\omega_j^U]$$

where $\omega_j^{\pm}$ gives interval weight of the j^{th} matrix.

STEP 4: Finding the crisp weights of the matrices [35].
The possibilities of $\omega_j^{\pm}$ to be more than $\omega_r^{\pm}$ can be determine by Equation (22) in accordance with equation (21).

(22)
$$p_{jr} = p(\omega_j^{\pm} \geq \omega_r^{\pm}) = \max\{1 - \max[\frac{m\omega_r^U - k\omega_j^L}{m\omega_r^U - k\omega_r^L + m\omega_j^U - k\omega_j^L}], 0\}$$

After the comparison of each pair of weights, the possibility matrix, determined by Equation (23).

(23)
$$M = \begin{bmatrix} M_{11} & \cdots & M_{1n} \\ \vdots & \ddots & \vdots \\ M_{n1} & \cdots & M_{nn} \end{bmatrix}$$

The crisp weight (ω_j) of each matrix is determined by Equation (24)

(24)
$$\omega_j = \frac{\sum_{r=1}^{n} p_{jr} + \frac{n}{2} - 1}{n(n-1)}$$

Intuitionistic fuzzy combinative distance-based assessment method (IFCODAS):
Euclidian and taxicab distance from the negative idol solution can weigh the overall performance with the help of CODAS. Nonetheless, ambiguous and vague human decrees cannot be clarified with traditional CODAS. With the combination of CODAS and Intuitionist fuzzy method, the new IFCODAS method has been used. Ghorabaee et al. [36]. Here IFCODAS was specified as:
STEP 1: Assume n matrices $(a_1 \cdots\cdots a_n)$ is used to evaluate the m alternative $(A_1 \cdots\cdots A_m)$. The administrators were requested to grade the substitutes with respect to each other through linguistic variables including (EP, UP, P, MP, F, MG, G, VG, EG). According to table 2 linguistic variables are shifted to intuitionist fuzzy numbers.

Table 2. Linguistic variables and their intuitionistic fuzzy numbers

Linguistic variables	Abbreviation	Intuitionistic fuzzy numbers
Extremely good	EG	(0.95, 0.05, 0)
Very good	VG	(0.85, 0.10, 0.05)
Good	G	(0.75, 0.15, 0.10)
Medium good	MG	(0.65, 0.25, 0.10)
Fair	F	(0.50, 0.40, 0.10)
Medium poor	MP	(0.35, 0.55, 0.10)
Poor	P	(0.25, 0.65, 0.10)
Very Poor	VP	(0.15, 0.80, 0.05)
Extremely Poor	EP	(0.05, 0.95, 0)

So the intuitionist fuzzy administrator making matrix may be determined as depicted in Equation (25)

(25)
$$D = \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{cccc} (\mu_{11}^x, \vartheta_{11}^x, \pi_{11}^x) & (\mu_{12}^x, \vartheta_{12}^x, \pi_{12}^x) & \dots & (\mu_{1n}^x, \vartheta_{1n}^x, \pi_{1n}^x) \\ (\mu_{21}^x, \vartheta_{21}^x, \pi_{21}^x) & (\mu_{22}^x, \vartheta_{22}^x, \pi_{22}^x) & \dots & (\mu_{2n}^x, \vartheta_{2n}^x, \pi_{2n}^x) \\ \vdots & \vdots & \ddots & \vdots \\ (\mu_{m1}^x, \vartheta_{m1}^x, \pi_{m1}^x) & (\mu_{m2}^x, \vartheta_{m2}^x, \pi_{m2}^x) & \dots & (\mu_{mn}^x, \vartheta_{mn}^x, \pi_{mn}^x) \end{array}$$

STEP2: The weighted intuitionistic fuzzy decision-making matrices are determined using Equations (26) and (27).

(26)
$$WD = \begin{array}{ccccc} & M_1 & M_2 & \dots & M_n \\ A_1 & \omega_1(\mu_{11}^x, \vartheta_{11}^x, \pi_{11}^x) & \omega_2(\mu_{12}^x, \vartheta_{12}^x, \pi_{12}^x) & \dots & \omega_n(\mu_{1n}^x, \vartheta_{1n}^x, \pi_{1n}^x) \\ A_2 & \omega_1(\mu_{21}^x, \vartheta_{21}^x, \pi_{21}^x) & \omega_2(\mu_{22}^x, \vartheta_{22}^x, \pi_{22}^x) & \dots & \omega_n(\mu_{2n}^x, \vartheta_{2n}^x, \pi_{2n}^x) \\ & \vdots & \vdots & \ddots & \vdots \\ A_m & \omega_1(\mu_{m1}^x, \vartheta_{m1}^x, \pi_{m1}^x) & \omega_2(\mu_{m2}^x, \vartheta_{m2}^x, \pi_{m2}^x) & \dots & \omega_n(\mu_{m2}^x, \vartheta_{m2}^x, \pi_{m2}^x) \end{array}$$

$$= \begin{array}{ccccc} & M_1 & M_2 & \dots & M_n \\ A_1 & (\mu_{11}, \vartheta_{11}, \pi_{11}) & (\mu_{12}, \vartheta_{12}, \pi_{12}) & \dots & (\mu_{1n}, \vartheta_{1n}, \pi_{1n}) \\ A_2 & (\mu_{21}, \vartheta_{21}, \pi_{21}) & (\mu_{22}, \vartheta_{22}, \pi_{22}) & \dots & (\mu_{2n}, \vartheta_{2n}, \pi_{2n}) \\ & \vdots & \vdots & \ddots & \vdots \\ A_m & (\mu_{m1}, \vartheta_{m1}, \pi_{m1}) & (\mu_{m2}, \vartheta_{m2}, \pi_{m2}) & \dots & (\mu_{mn}, \vartheta_{mn}, \pi_{mn}) \end{array}$$

(27)
$$\mathrm{wd}_{ij} = (\mu_{ij}, \vartheta_{ij}, \pi_{ij}) = \omega_j(\mu_{ij}^x, \vartheta_{ij}^x, \pi_{ij}^x) = (1-(1-\mu_{ij}^x)^{\omega_j}, (\vartheta_{ij}^x)^{\omega_j}, (1-\mu_{ij}^x)^{\omega_j} - (\vartheta_{ij}^x)^{\omega_j})$$

STEP3: The negative ideal solution (NIS) is determined by Equations (28-32) .

(28)
$$\mathrm{NIS}_j = (\mu_j, \vartheta_j, \pi_j), j = 1,2,3,\dots,n$$

(29)
$$\mathrm{t} = arg_i \min\ (\mu_{ij})$$

(30)
$$\mu_j = \mu_{tj}$$

(31)
$$\vartheta_j = \vartheta_{tj}$$

(32)
π_j=1-μ_tj-ϑ_tj

STEP-4: The Euclidean (E) and harmonic (H) distances are calculated using Equations (33, 34).

(33)
$$\mathrm{E}\ (\mathrm{wd}_{ij}, NIS_J) = \sqrt{\frac{1}{2}\sum_{j=1}^{n}(\mu_{ij}-\mu_j)^2 + (\vartheta_{ij}-\vartheta_j)^2 + (\pi_{ij}-\pi_j)^2]}$$

(34)
$$\mathrm{H}\ (\mathrm{wd}_{ij}, NIS_J) = \frac{1}{2}\sum_{J=1}^{N}(|\mu_{ij}-\mu_j| + |\vartheta_{ij}-\vartheta_j| + |\pi_{ij}-\pi_j|)$$

STEP 5: The relative assessment matrix (R) is determined by using Equations (35-37).

(35)
$$\mathrm{R} = \{r_{ik}\}$$

(36)
$$r_{ik} = [E(wd_{ij}, N) - E(wd_{kj}, NIS_j)] + \emptyset[E(wd_{ij}, NIS_j) - E(wd_{kj}, NIS_j)] \times [H(wd_{ij}, NIS_j) - H(wd_{kj}, NIS_j)]$$

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(37) $$\emptyset\left[E\left(wd_{ij}, NIS_j\right) - E\left(wd_{kj}, NIS_j\right)\right] = \begin{cases} 1\ if\ -\tau \leq E\left(wd_{ij}, NIS_j\right) - E\left(wd_{kj}, NIS_j\right) \leq \tau \\ 0\ \ if\ others \end{cases}$$

STEP 6: The final assessment score (S_i) of each alternative is calculated using Equation 38.

(38) $$S_i = \sum_{k=1}^{m} r_{ik}$$

Case Study:
Five nanoparticles viz. metal based nanofluids (A1), carbon-based nanoparticles (A2), ceramic based nanoparticles (A3), polymeric nanoparticles (A4), and lipid-based nanoparticles (A5), by the planned intuitionistic fuzzy multi-criteria decision-making method have been studied in the present study. These five nanoparticles can be designated as:
Metal Based Nanoparticles: Metal nanoparticles are thriving from metal precursors and manufactured by chemical, electrochemical, or photochemical method. The metal nanoparticles include gold (Au), nickel (Ni), silver (Ag), zinc oxide (ZnO), silica (SiO_2), and titanium dioxide (TiO_2) etc.

Carbon Nanoparticles: Carbon nanoparticles are highly advantageous in order to augment the crack initiation of energy threshold to advance impact capacity and post impact behaviour. It consists of carbon nanotubes (CNTs), zigzag nanotubes, and chiral carbon nanotubes.
Ceramic Nanoparticles: These are inorganic solid build-up of carbonates, carbides, oxides and phosphates with rich chemical inertness and heat resistances properties.
Polymeric Nanoparticles: They are organic based nanoparticles with nanosphere or nano capsular shaped structure. The most widely used polymeric are polylactide, polylactide-polyglycolide copolymers etc.
Lipid Nanoparticles: They are embraced of solid core which is designed of metrics and lipid accommodates soluble lipophilic molecules. Their shape is spherical while diameter varies from 10-100nm.
Out of four categories of assessment aspects (cost, efficiency, technical and environmental effect) the eligibility have been engaged for sustainability estimate capital cost (C1), operating cost (C2), and durability cost (C3) in cost aspect (C), thermal efficiency (E1), effective efficiency (E2), and exergetic efficiency in efficiency aspect (E), technical complexity (T1), technical reliability (T2), in technical aspect (T), and risk to ecosystem (EE1), wastage utilization(EE2), toxic effect on environment (EE3) in environment aspect (EE). The weight of four criteria and categories has been firstly identified by IAHP. The following steps of IAHP have been described through example:
Step 1: Weights of four assessment aspects can be firstly identified through interval pair-wise comparison matrix as shown in Table no. 3.

Table 3 Interval pair-wise comparison matrix for determining categories weight

	Cost	Efficiency	Technology	Environment
C	(1, 1)	(3, 7)	(1, 3)	(5, 7)
E	(1/7, 1/3)	(1, 1)	(1/5, 1/2)	(3, 5)
T	(1/3, 1)	(2, 5)	(1, 1)	(3, 7)
EE	(1/7, 1/5)	(1/5, 1/3)	(1/7, 1/3)	(1, 1)

Step 2: According to Table no. 3 the result of two crisp nonnegative matrices can be identified and expressed in Equation (39) and Equation (40).

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(39)

$$P_L = \begin{bmatrix} p_{11}^- & p_{12}^- & p_{13}^- & p_{14}^- \\ p_{21}^- & p_{22}^- & p_{23}^- & p_{24}^- \\ p_{31}^- & p_{32}^- & p_{33}^- & p_{34}^- \\ p_{41}^- & p_{42}^- & p_{43}^- & p_{44}^- \end{bmatrix} = \begin{bmatrix} 1 & 3 & 1 & 5 \\ 1/7 & 1 & 1/5 & 3 \\ 1/3 & 2 & 1 & 3 \\ 1/7 & 1/5 & 1/7 & 1 \end{bmatrix}$$

(40)

$$P_U = \begin{bmatrix} p_{11}^+ & p_{12}^+ & p_{13}^+ & p_{14}^+ \\ p_{21}^+ & p_{22}^+ & p_{23}^+ & p_{24}^+ \\ p_{31}^+ & p_{32}^+ & p_{33}^+ & p_{34}^+ \\ p_{41}^+ & p_{42}^+ & p_{43}^+ & p_{44}^+ \end{bmatrix} = \begin{bmatrix} 1 & 7 & 3 & 7 \\ 1/3 & 1 & 1/2 & 5 \\ 1 & 5 & 1 & 7 \\ 1/5 & 1/3 & 1/3 & 1 \end{bmatrix}$$

By the above matrices, weight W_L and W_U can be found by the geometric-method and represented in Equation (41) and Equation (42).

(41) $$W_L = \{0.4862, 0.1462, 0.3013, 0.0662\}$$

(42) W_U = {0.4726, 0.1401, 0.3316, 0.0558}

Step 3: The s and t are determined from Equation (43) and Equation (44) respectively.

(43)

$$s = \sqrt{\sum_{j=1}^{4} \frac{1}{\sum_{i=1}^{4} p_{ij^+}}} = \sqrt{\frac{15}{38} + \frac{3}{40} + \frac{6}{29} + \frac{1}{20}} = 0.8524$$

(44)

$$t = \sqrt{\sum_{j=1}^{4} \frac{1}{\sum_{i=1}^{4} p_{ij^-}}} = \sqrt{\frac{21}{34} + \frac{5}{31} + \frac{35}{82} + \frac{1}{12}} = 1.1354$$

Equations (45) to (48) represents the results of four assessment aspects of energy storage technologies of interval weights sustainability of Equation (21).

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(45) $$W_C^{\pm} = \{0.8524 \times 0.4862 \;\; 1.1354 \times 0.4726\} = \{0.4145 \;\; 0.5365\}$$

(46) $$W_E^{\pm} = \{0.8524 \times 0.1462 \;\; 1.1354 \times 0.1401\} = \{0.1246 \;\; 0.1591\}$$

(47) W_T^±={0.8524 × 0.3013 1.1354 × 0.3316}={0.2568 0.3764}

(48) $$W_{EE}^{\pm} = \{0.8524 \times 0.0662 \;\; 1.1354 \times 0.0558\} = \{0.0564 \;\; 0.0634\}$$

Step 4: By analysing the weight of each pair of division from Equation (22), the features of the possibility matrix are found. Assume that the possibility of $W_E^{\pm}$ be more than$W_C^{\pm}$ as an example:

(49)

$$P(W_E^{\pm} \geq W_C^{\pm}) = Max\left\{1 - \max\left[\frac{W_E{}^{U} - W_C{}^{L}}{W_E{}^{U} - W_E{}^{L} + W_C{}^{U} - W_C{}^{L}}, 0\right], 0\right\}$$

$$P\left(W_{E2}^{\pm} \geq W_{C1}^{\pm}\right) = Max\left\{1 - \max\left[\frac{0.1591 - .04145}{0.1591 - 0.1246 + 0.5365 - 0.4145}, 0\right], 0\right\} = 0$$

In correspondingly, Equation (50) presents the results of possibility matrix.

(50)

$$M = \begin{bmatrix} & C & E & T & EE \\ C & 0.5000 & 1.0000 & 1.0000 & 1.0000 \\ E & 0 & 0.5000 & 0 & 1.0000 \\ T & 0 & 1.0000 & 0.5000 & 1.0000 \\ EE & 0 & 0 & 0 & 0.5000 \end{bmatrix}$$

According to Equation (51) the results of crisp weight of each metric are shown in Equations (51) to (54)

(51) $$W_C = \frac{\sum_{r=1}^{4} M_{1r} + \frac{n}{2} - 1}{n(n-1)} = \frac{0.5000 + 1.0000 + 1.0000 + 1.0000 + \frac{4}{2} - 1}{4(4-1)} = 0.3570$$

(52) $$W_E = \frac{\sum_{r=1}^{4} M_{2r} + \frac{n}{2} - 1}{n(n-1)} = \frac{0 + 0.5000 + 0 + 1.0000 + \frac{4}{2} - 1}{4(4-1)} = 0.2083$$

(53) $$W_T = \frac{\sum_{r=1}^{4} M_{3r} + \frac{n}{2} - 1}{n(n-1)} = \frac{0 + 1.0000 + 0.5000 + 1.0000 + \frac{4}{2} - 1}{4(4-1)} = 0.2917$$

(54) $$W_{EE} = \frac{\sum_{r=1}^{4} M_{4r} + \frac{n}{2} - 1}{n(n-1)} = \frac{0 + 0 + 0 + 0.5000 + \frac{4}{2} - 1}{4(4-1)} = 0.1250$$

0.3570, 0.2083, 0.2917, and 0.1250, respectively shows the weights of the cost, efficiency, technological, and environmental effect assessment aspects. Likewise, Tables 4-7 depict the interval pair-wise comparison matrix of weights for each criterion.

Table 4. The cost aspect weights of the three criteria's

	C1	C2	C3
C1	(1,1)	(1/3,1)	(3,5)
C2	(1,2)	(1,1)	(1,3)
C3	(1/5,1/3)	(1/3,1)	(1,1)
Weight	0.3333	0.5000	0.1667

Table 5. The efficiency aspect weights of the three criteria's

	E1	E2	E3
E1	(1,1)	(1/2,1)	(3,5)
E2	(1,2)	(1,1)	(1,3)
E3	(1/5,1/3)	(1/3,1)	(1,1)
Weight	0.3333	0.5000	0.1667

Table 6. The technical aspect weights of the two criteria's

	T1	T2
T1	(1,1)	(1,5)
T2	(1/5,1)	(1,1)
Weight	0.750	0.250

Table 7. The weights of the three criteria of environmental effect aspect

	EE1	EE2	EE3
EE1	(1,1)	(1/5,1)	(1/3,1)
EE2	(1,5)	(1,1)	(1/4,1/2)
EE3	(1,3)	(2,4)	(1,1)
Weight	0.1667	0.3333	0.5000

In order to evaluate the weight of four classes, the categories of the global weight of eleven metrics and the result have been displayed in Table 8.

Table 8. The global weights of the eleven criteria's

Criteria	C1	C2	C3	E1	E2	E3	EE1	EE2	EE3	T1	T2
Weight	0.125	0.1875	0.0625	0.0694	0.1041	0.0347	0.0208	0.0416	0.0625	0.2187	0.073

To grade different nanoparticles, administrators utilized the linguistic variable firstly, to each of the matrix for sustainability assessment by involving full team expertise and researchers. The results have been encapsulated in Table 9.

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Table 9. The interpretation of the five nanoparticles using linguistic variables

	A1	A2	A3	A4	A5
C1	F	MP	MG	P	VP
C2	F	MP	G	MG	P
C3	MP	P	F	MG	G
E1	VP	EP	MP	P	F
E2	MP	F	G	MG	P
E3	P	EP	MP	P	VP
EE1	VG	EG	G	MG	P
EE2	VG	EG	MG	G	P
EE3	G	VG	MG	F	F
T1	MG	MP	F	F	P
T2	EG	VG	MG	G	F

After that, linguistic variables have been converted into β according to Table 1. For example, “EG, VG……VP, EP” in Table 9. can be rearranged into “(0.95, 0.05, 0)(0.85, 0.10, 0.05)……(0.15, 0.80, 0.05)(0.05, 0.95, 0)”, and shown in Table 10.

Table 10. Performances of four energy storage technologies

	A1	A2	A3	A4	A5
C1	(0.50, 0.40, 0.10)	(0.35, 0.55, 0.10)	(0.65, 0.25, 0.10)	(0.25, 0.65, 0.10)	(0.15, 0.80, 0.05)
C2	(0.50, 0.40, 0.10)	(0.35, 0.55, 0.10)	(0.75, 0.15, 0.10)	(0.65, 0.25, 0.10)	(0.25, 0.65, 0.10)
C3	(0.35, 0.55, 0.10)	(0.25, 0.65, 0.10)	(0.50, 0.40, 0.10)	(0.65, 0.25, 0.10)	(0.75, 0.15, 0.10)
E1	(0.15, 0.80, 0.05)	(0.05, 0.95, 0)	(0.35, 0.55, 0.10)	(0.25, 0.65, 0.10)	(0.50, 0.40, 0.10)
E2	(0.35, 0.55, 0.10)	(0.50, 0.40, 0.10)	(0.75, 0.15, 0.10)	(0.65, 0.25, 0.10)	(0.25, 0.65, 0.10)
E3	(0.25, 0.65, 0.10)	(0.05, 0.95, 0)	(0.35, 0.55, 0.10)	(0.25, 0.65, 0.10)	(0.15, 0.80, 0.05)
EE1	(0.85, 0.10, 0.05)	(0.95, 0.05, 0)	(0.75, 0.15, 0.10)	(0.65, 0.25, 0.10)	(0.25, 0.65, 0.10)
EE2	(0.85, 0.10, 0.05)	(0.95, 0.05, 0)	(0.65, 0.25, 0.10)	(0.75, 0.15, 0.10)	(0.25, 0.65, 0.10)
EE3	(0.75, 0.15, 0.10)	(0.85, 0.10, 0.05)	(0.65, 0.25, 0.10)	(0.50, 0.40, 0.10)	(0.50, 0.40, 0.10)
T1	(0.65, 0.25, 0.10)	(0.35, 0.55, 0.10)	(0.50, 0.40, 0.10)	(0.50, 0.40, 0.10)	(0.25, 0.65, 0.10)
T2	(0.95, 0.05, 0)	(0.85, 0.10, 0.05)	(0.65, 0.25, 0.10)	(0.75, 0.15, 0.10)	(0.50, 0.40, 0.10)

The weighted intuitionistic fuzzy decision-making matrix is determined by Equation (27). Suppose that the element “(0.50, 0.40, 0.10)” in cell (1, 1) which show metal-based nanoparticles (A1) in favour of capital cost (C1)

(55)

$$wd_{11} = (\mu_{11}, v_{11}, \pi_{11}) = \omega_1(\mu^*_{11}, v^*_{11}, \pi^*_{11})$$

$$wd_{11} = [(1-(1-\mu^*_{11})^{\omega 1}), (v^*_{11})^{\omega 1}, ((1-\mu^*_{11})^{\omega 1} - (v^*_{11})^{\omega 1})]$$

$$wd_{11} = [(1-(1-0.50)^{0.1249}), (0.40)^{0.1249}, ((1-0.50)^{0.1249} - (0.40)^{0.1249})]$$

$$\mathrm{wd}_{11} = (0.0829, 0.8918, 0.0252)$$

where wd_{11} is first cell of Table 11.
Similarly, all cells of institution fuzzy numbers are transformed to weighted institution fuzzy decision making metrics and represented in Table 11.

Table 11. The weighted intuitionistic fuzzy decision-making matrix

	A1	A2	A3	A4	A5
C1	(0.0829, 0.8918, 0.0252)	(0.0523, 0.9280, 0.0195)	(0.1228, 0.8410, 0.0360)	(0.0352, 0.9476, 0.0170)	(0.0201, 0.9725, 0.0073)
C2	(0.1218, 0.8421, 0.0359)	(0.0775, 0.8939, 0.0284)	(0.2288, 0.7006, 0.0704)	(0.1786, 0.7712, 0.0502)	(0.0525, 0.9224, 0.0250)
C3	(0.0265, 0.9634, 0.0102)	(0.0178, 0.9734, 0.0087)	(0.0423, 0.9443, 0.0132)	(0.0635, 0.9170, 0.0194)	(0.0829, 0.8881, 0.0288)
E1	(0.0112, 0.9846, 0.0042)	(0.0035, 0.9964, 0)	(0.0294, 0.9593, 0.0112)	(0.0197, 0.9705, 0.0096)	(0.0469, 0.9383, 0.0146)
E2	(0.0438, 0.9562, 0)	(0.0696, 0.9090, 0.0213)	(0.1343, 0.8207, 0.0448)	(0.1035, 0.8656, 0.0308)	(0.0295, 0.9561, 0.0143)
E3	(0.0099, 0.9851, 0.0049)	(0.0017, 0.9982, 0)	(0.0148, 0.9794, 0.0056)	(0.0099, 0.9851, 0.0049)	(0.0056, 0.9922, 0.0020)
EN1	0.0386, 0.9532, 0.0080)	(0.0604, 0.9395, 0)	(0.0284, 0.9613, 0.0102)	(0.0215, 0.9715, 0.0068)	(0.0059, 0.9910, 0.0029)
EN2	(0.0758, 0.9086, 0.0154)	(0.1171, 0.8828, 0)	(0.0427, 0.9439, 0.0134)	(0.0560, 0.9241, 0.0198)	(0.0118, 0.9822, 0.0058)
EN3	(0.0829, 0.8881, 0.0288)	(0.1118, 0.8659, 0.0223)	(0.0635, 0.9171, 0.0194)	(0.0423, 0.9443, 0.0132)	(0.0423, 0.9443, 0.0132)
T1	(0.2051, 0.7384, 0.0563)	(0.0899, 0.8774, 0.0326)	(0.1406, 0.8184, 0.0409)	(0.1406, 0.8184, 0.0409)	(0.0609, 0.9101, 0.0289)
T2	(0.1961, 0.8038, 0)	(0.1291, 0.8454, 0.0253)	(0.0736, 0.9038, 0.0224)	(0.0961, 0.8708, 0.0330)	(0.0492, 0.9353, 0.0153)

The relative interpretation of five different nanoparticles (A1, A2, A3, A4, and A5) with respect to C1 are (0.0829, 0.8918, 0.0252), (0.0523, 0.9280, 0.0195), (0.1228, 0.8410, 0.0360), (0.0352, 0.9476, 0.0170) and (0.0201, 0.9725, 0.0073), respectively. According to Equation (27), it could be obtained that

(56) $$\mathrm{t} = \underset{i=1,2,3,4.5}{\mathrm{argmin}}\,(0.0829, 0.0523, 0.1228, 0.0352, 0.0201) = 5$$

Then, the three elements in the NIS in favour of C1 can be evaluated:

(57) $$\mu_j = \mu_{5j} = 0.0201$$

(58) $$\mathrm{v}_j = \mathrm{v}_{5j} = 0.9725$$

(59) $$\pi_j = 1 - \mu_{5j} - v_{5j} = 1 - 0.0201 - 0.9725 = 0.0073$$

Similarly, all the NIS of nanoparticles have been expressed in Table 12.

Table 12. The weighted intuitionistic fuzzy decision-making matrix

Criteria's		NIS	
C1	0.0201	0.9725	0.0073
C2	0.0525	0.9224	0.0250
C3	0.0178	0.9734	0.0087
E1	0.0035	0.9964	0
E2	0.0295	0.9561	0.014
E3	0.0017	0.9982	0
EE1	0.0059	0.9910	0.0029
EE2	0.0118	0.9822	0.0058
EE3	0.0423	0.9443	0.0132
T1	0.0609	0.9100	0.0289
T2	0.0492	0.9353	0.0153

After the determination of the NIS, we have to find the Euclidean and Hamming distance for each nanoparticle from NIS as expressed in Equations (33, 34) and result as shown in Table 13.

Table 13. Euclidean and Hamming distance

	Ei	Hi
1	0.3612	1.333
2	0.2502	0.9437
3	0.4088	1.5841
4	0.2979	1.1919

The relative assessment matrix as presented in Equation (61) has been determined using Equations (35) to (37) by taking threshold value (τ) as 0.05.

(60)

$$R = \begin{array}{c|ccccc} & A1 & A2 & A3 & A4 & A5 \\ A1 & 0 & 0.1109 & -0.2032 & 0.0634 & 0.2291 \\ A2 & -0.1109 & 0 & -0.1585 & -0.2005 & 0.1182 \\ A3 & 0.2032 & 0.1585 & 0 & 0.1109 & 0.2767 \\ A4 & -0.0634 & 0.2005 & -0.1109 & 0 & 0.1658 \\ A5 & -0.2291 & -0.1182 & -0.2767 & -0.1658 & 0 \end{array}$$

Then, the final assessment score of each nanoparticle have been determined using Equation (38) and as shown in Equations (61) to (65).

(61) $$S_1 = 0 + 0.1109 + (-0.2032) + 0.0634 + 0.2291 = 0.2002$$

(62) $$S_2 = (-0.1109) + 0 + (-0.1585) + (-0.2005) + 0.1182 = -0.3517$$

(63) $$S_3 = 0.2032 + 0.1585 + 0 + 0.1109 + 0.2767 = 0.7493$$

(64) $$S_4 = (-0.0634) + 0.2005 + (-0.1109) + 0 + 0.1658 = 0.1920$$

(65) $$S_5 = (-0.2291) + (-0.1182) + (-0.2767) + (-0.1658) + 0 = -0.7898$$

As per the final assessment scores of the five nanoparticles, the carbon based (A3) has been identified as the most sustainable one, followed by metal based (A1), polymeric (A4),ceramic (A2), and lipid based (A5) from the outmost sustainable one to the least sustainable. The outcome of distinguishing carbon based has been established to be the most sustainable.

Results and discussion

For the ranking of five nanoparticles, the single criterion has been used as per relative interpretation on each of the eleven criteria. The prescription of the single criterion analysis method is as follows:

Assume that $\gamma = (\mu_\gamma, v_\gamma, \pi_\gamma)$ and $\beta = (\mu_\beta, v_\beta, \pi_\beta)$ are two βs to characterize the relative interpretation of two alternative nanoparticles A and B on an estimation benchmark, respectively. The highly superior nanoparticle between A and B alternatives can be resolved as per the following rules.

1) If $R_\gamma = \mu_\gamma - v_\gamma < R_\beta = \mu_\beta - v_\beta$ then $\gamma = (\mu_\gamma, v_\gamma, \pi_\gamma)$ is smaller than $\beta = (\mu_\beta, v_\beta, \pi_\beta)$ and A is inferior to B.
2) If $R_\gamma = \mu_\gamma - v_\gamma < R_\beta = \mu_\beta - v_\beta$, than;
   a. $r_\gamma = \mu_\gamma + v_\gamma = r_\beta = \mu_\beta + v_\beta$, then, $\gamma = (\mu_\gamma, v_\gamma, \pi_\gamma)$ is equal to$\beta = (\mu_\beta, v_\beta, \pi_\beta)$, and A is indifferent to B;
   b. $r_\gamma = \mu_\gamma + v_\gamma < r_\beta = \mu_\beta + v_\beta$, then, $\gamma = (\mu_\gamma, v_\gamma, \pi_\gamma)$ is smaller than$\beta = (\mu_\beta, v_\beta, \pi_\beta)$, and A is inferior to B;

c. $r_\gamma = \mu_\gamma + v_\gamma > r_\beta = \mu_\beta + v_\beta$, then, $\gamma = (\mu_\gamma, v_\gamma, \pi_\gamma)$ is greater than$\beta = (\mu_\beta, v_\beta, \pi_\beta)$, and A is superior to B;

where R_γ and R_β epitomize the scores of the intuitionistic fuzzy sets, $\gamma = (\mu_\gamma, v_\gamma, \pi_\gamma)$ and $\beta = \left(\mu_\beta, v_\beta, \pi_\beta\right)$, respectively r_γ and r_β are the accuracy in intuitionistic fuzzy sets, $\gamma = (\mu_\gamma, v_\gamma, \pi_\gamma)$ and $\beta = (\mu_\beta, v_\beta, \pi_\beta)$, respectively.

For the ranking of five substitute nanoparticles, Table 14 and Fig. 2 has been presented on the basis of the results of single-criterion method. It is clearly visible that the positioning of these five nanoparticles based on contrasting criterion is divergent. Thus, the administrator necessitates the unique sustainability sequence of individual substitute aggregating the execution order of these five alternatives on eleven evaluation criteria into generic content which helps the administrators to accomplish their objective.
Value of τ is distorted to discover the dissimilarity of the sustainability ranking of the five alternative nanoparticles because of threshold value influence, and the results have been presented in Table 15.

Table 14. The ranking of the five nanofluids using the single-criterion analysis method.

	A1	A2	A3	A4	A5
C1	4	2	3	5	1
C2	5	1	4	3	2
C3	5	3	2	1	4
E1	5	1	4	2	3
E2	2	1	4	3	5
E3	3	1	5	4	2
EN1	5	1	3	4	2
EN2	4	2	3	5	1
EN3	4	2	3	5	1
T1	3	2	5	4	1
T2	1	5	2	4	5

Table 15. The results of the analysis of the threshold value on the sustainability ranking of the five nanoparticles

	A1	A2	A3	A4	A5
Final assessment score	0.2002	-0.3517	0.7493	0.1920	-0.7898
Ranking	2	4	1	3	5

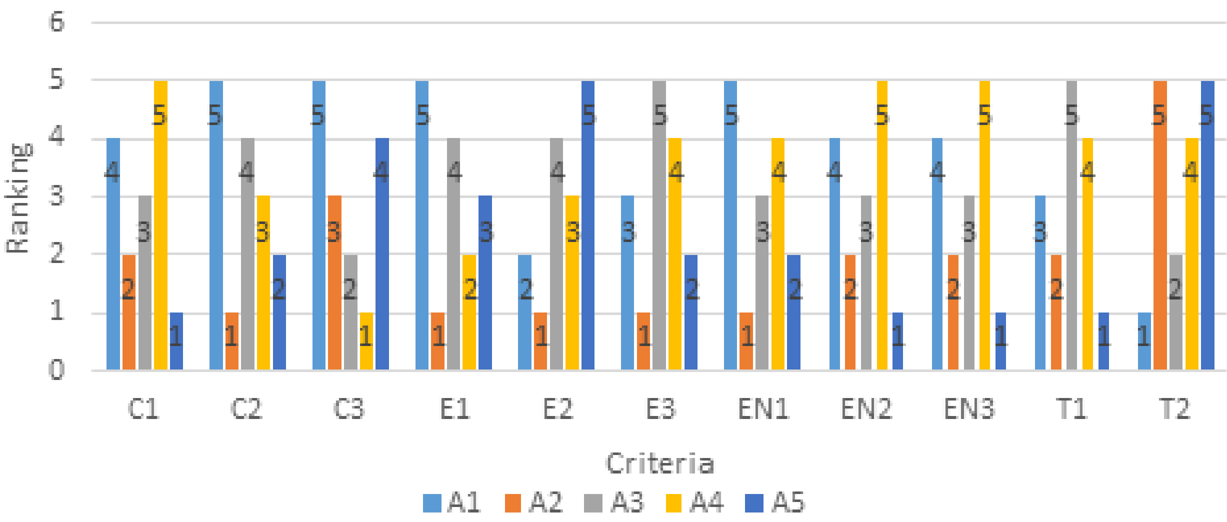

Fig. 2. Ranking of criteria for different nanoparticles

Impact

The present analysis of a heat exchanger with nanomaterial as working fluid is carried using the intuitionistic fuzzy combative distance-based assessment ($IFCODAS$) in collaboration with Intuitionistic fuzzy set (IFS). The major aim is to determine the sustainability of nanoparticles in the system. The results reveal that carbon-based nanoparticles significantly provide the reliable and sustainable thermal system than other nanoparticles. This type of assessment approach will lead to the development of an effective system that works with the best suited parameters. The determination of reliable and sustainable parameter of a system will make is economically viable and trustworthy, that will lead to utilization of the resources to full extent as well as the present technique will lead to find out the dominating parameters without much focusing on the experimental processes, as it will provide a dominating value for a parameter. The real practical application of this model will lead to practically reducing the number of experimental runs and thus will fetch benefit in time saving and monetary as well. Apart from this the evaluation criterions consist of environmental aspect that will suggest the best suited nanomaterial that does not raises the environmental concern. The present analysis will lead to figure out the nanoparticle usage on the basis of environmental effect and will lead to develop a reliable system design of a heat exchanger. Beside the number of advantages, a setback in this system is the complexity of the design that is used to study the focused parameter on the basis of selected criterions.

Conclusion

A fresh model of suitability of nanoparticles scheme to grasp multi-criteria decision-making problems has been foreshadowed in the present study. Multi-criteria decision-making (MCDM) has been progressively applied to numerous real-world predicaments. Several methods and techniques in order to cope up with the quandaries to handle multi-criteria decision-making problems have been proposed by the researchers. The proposed method intends to evaluate the alternatives, five nanoparticles (carbon based, ceramic, metal nanoparticles, polymeric, and lipid) with the help of intuitionistic fuzzy combative distance-based assessment method by giving them ranking on the basis of their assessment. Discussing absolute judgment scores of various nanoparticles, the most sustainable resulted in carbon based (A3). Amongst the five nanoparticles, carbon-based nanoparticle has been found to the most sustainable owing to the reason that the carbon-based nanoparticle is composed of unpolluted carbons and holds astounding mechanical properties, electrical conductivity and heat conductivity with pure carbons, consequently demonstrating ecological gregariousness, superior conductivity, heat steadiness, and stumpy toxicity. It can thus be stated that the projected method is proficient in order to deal with MCDM impediments, as held in unison with the results of this study.

Conflict of interest

There are no conflicts to declare.

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BIOMASS DELIGNIFICATION WITH GREEN SOLVENTS TOWARDS LIGNIN VALORISATION: IONIC LIQUIDS VS DEEP EUTECTIC SOLVENTS

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Abstract
The use of renewable resources as feedstocks to ensure the production of goods and commodities for society has been explored in the last decades to switch off the overexploited and pollutant fossil-based economy. Today there is a strong movement to set bioeconomy as priority, but there are still challenges and technical limitations that must be overcome in the first place, particularly on biomass fractionation. For biomass to be an appellative raw material, an efficient and sustainable separation of its major components must be achieved. On the other hand, the technology development for biomass valorisation must follow green chemistry practices towards eco-friendly processes, otherwise no environmental leverage over traditional petrochemical technologies will be acquired. In this context, the application of green solvents, such as ionic liquids (ILs) and deep eutectic solvents (DES), in biomass fractionation is envisaged as promising technology that encompasses not only efficiency and environmental benefits, but also selectivity, which is a crucial demand to undertake cascade processes at biorefinery level. In particular, this article briefly discusses the disruptive achievements upon the application of ILs and DES in biomass delignification step towards an effective and selective separation of lignin from polysaccharides. The different physicochemical properties of these solvents, their interactions with lignin and their delignification capacity will be scrutinized, while some highlights will be given to the important characteristics of isolated lignin fractions for further valorisation. The advantages and disadvantages between ILs and DES in biomass delignification will be contrasted as well along the article.

Keywords
lignin, lignocellulosic biomass, green solvents, biomass delignification, valorisation

Introduction
The growth and technological evolution of humanity have brought economic and environmental dilemmas with massive challenges to health and welfare of society. The deficient resource management is one of the major bottlenecks to be solved and has a colossal handicap on our biosphere. The intensive exploration of non-renewable fossil resources in the last decades has increased CO_2 emissions, destruction of ecosystems, pollution of rivers and oceans, deforestation and biodiversity threats to global levels that undermines sustainable development of future generations. The scientific evidence has shown that the point of no return can be nearby and drastic moves are urgent to decline this fate to our planet. In this sense, the use of renewable resources to replace fossil-based feedstocks is seen as priority to undercut a pollutant and non-sustainable growth and to move forward with bioeconomy, a more sustainable model of development. Bioeconomy emerges as an alternative approach that deals with the maximal exploitation of biomass and other bio-based resources as starting materials to produce energy, fuels, chemicals and materials fulfilling society needs. The idea is to cover efficient processes for biomass fractionation and conversion into these commodities by the so-called biorefineries, analogous to current petroleum refineries [1]. The industrial activities that convert every single fraction of crude oil into all the commodities we know today have been intensively developed and explored since the industrial revolution at 18th century. On the contrary, the technological development and readiness upon biomass processing and valorisation is quite lower and to push it to similar levels is a major challenge expected for the next few years. Therefore, high investment and straightforward efforts are needed to leverage sustainable processes and innovative technologies for the conversion and valorisation of biological and renewable resources, including biomass [2].

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As one of the most abundant renewable resources in the world, lignocellulosic biomass is found mainly as agriculture residues (*e.g.* wheat straw, corn stover, sugarcane bagasse, etc.), energy crops (*e.g.* switchgrass, elephant grass, miscanthus, etc.) and forestry materials (*e.g.* wood, tree branches, tree bark, etc.). In Europe, their availability exceeds 1 billion dry tonnes per year [3], thus their interest as primary resource and raw material in industrial processes is obviously high. The composition of lignocellulosic biomass is mostly devoted to three main macromolecular components, namely cellulose (40-50 wt%), hemicelluloses (10-30wt%) and lignin (15-35 wt%)[4]. Cellulose is a semicrystalline homopolysaccharide constituted by cellobiose as repeating unit, while hemicelluloses represent amorphous heteropolysaccharides constituted by different hexoses, pentoses and uronic acids. In contrast to cellulose, the structure and chemical composition of hemicelluloses are variable and are dependent on their biomass source. Both cellulose and hemicelluloses compose the polysaccharide fraction of lignocellulosic biomass and play essentially structural roles. In contrast, lignin is a random aromatic polymer constituted by phenylpropanoid units and the most conventional ones are *p*-coumaryl, coniferyl and sinapyl alcohols [4]. Recently, other aromatic units, like flavonoids, hydroxystilbenes, among others, have been also reported to make part of lignin structure [5]. These units are randomly linked by several types of C-O (*e.g.* β-O-4 and α-O-4) and C-C (*e.g.* β-β, β-5 and β-1) chemical bonds. Lignin not only gives structural rigidity to plant biomass, but also exhibits protective role against any external biota. Other fractions, such as proteins, phenolic, lipophilic and inorganic compounds also exist in lignocellulosic biomass, although at much lower content (< 5 wt%). The way biomass polysaccharides and lignin are linked (intermolecular and covalent bonds) leads to an intricate and complex three-dimensional matrix difficult to disrupt by means of any physical, chemical and/or biological treatment. This recalcitrance is one of the key aspects that hinders the profit in generating bioproducts from these raw materials and must be overcome with efficient fractionation processes. Indeed, there are still technological hurdles to achieve maximal exploitation of lignocellulosic biomass, while today the concerns related to the environmental impact of developed technologies must be taken into account as well.

The fractionation and isolation of biomass polysaccharides have been tackled for a long time. Pulp and paper manufacturing was the first industry to valorise lignocellulosic biomass since 19th century [6]. The isolation of cellulose pulp by removing lignin from wood is the main focus of these industries to produce paper at different grades. Nowadays, there are several well-known pulp and paper processes at industrial scale, including Kraft, Soda and Sulfite pulping, that uses water and inorganic chemicals, like NaOH, Na_2S, SO_2 and alkali metals, to enable wood delignification efficiently and to maintain cellulose fibres intact and at desired strength. Cellulose pulp has been used mostly in the manufacture of paper and carboards, but an increasing interest to produce novel cellulose-based materials to substitute petrochemical ones has been observed lately as a clear movement to increase sustainability [7]. This kind of strategy is expected to place pulp and paper industries in the path of the biorefinery concept and could be a model to follow in the bioeconomy activity. On the other hand, the interest in converting polysaccharides from agriculture residues and energy crops towards 2G bioethanol at industrial scale has been approached by few companies in the current century. In this case, hydrothermal (steam), acid (sulfuric), alkaline (ammonia) and organosolv (acetic acid, ethanol) treatments have been applied to lignocellulosic biomass to open up the biomass matrix, allowing for better accessibility of cellulolytic enzymes (celluloses and xylanases) towards polysaccharide hydrolysis into C5 and C6 sugars. The monosaccharide enriched hydrolysate is then used as feed substrate to microorganisms capable of converting those carbohydrates into ethanol. Other biotechnological approaches aiming at the conversion of C5 and C6 sugars into value added chemicals, including butanol, organic acids, among others has been approached, yet at lab and/or pilot scales.

Bearing this in mind, pulp and paper companies and 2G bioethanol industries have shared a similar principle: to raise the value of biomass carbohydrates. In their framework of activities, lignin is considered as by-product and today no real value has been extracted from it. In case of pulp and paper companies, the black liquor resulting from wood delignification is burnt in boilers to recover the initial inorganic chemicals. This operation enables the combustion of lignin and other organic fractions present in the black liquor to generate energy, which is directly supplied to the factory and/or sold to the grid [8]. Similar approach has been delivered by 2G ethanol industries, in which lignin can be incinerated in combined heat and power units [9]. Although such bio-based companies refer to those integrated processes as self-sufficient in terms of energy requirements, the long-term sustainability of this practice might be questioned. Lignin is an aromatic polymer and may represent between 20-35 wt% of initial lignocellulosic feedstocks (wood or others). Therefore, as an isolated material, lignin has the potential to replace the aromatic fraction of fossil sources in the formulation of chemicals and materials. However, one of the drawbacks that has led to decline a higher valorisation of lignin rather than its combustion

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is the quality of isolated samples. For instance, sulfur-based reagents (Na_2S and SO_2) along with high temperatures (150-170 ºC) are often applied in pulp and paper making to achieve wood delignification. This energy intensive process enables the isolation of a low-value sulfur-based lignin with extensive chemical modification characterised by condensed macromolecules, high molecular dispersion and low number of functional groups (loss of functionality). These are clearly undesired characteristics for its further application hindering an appropriate valorisation.

The strategy for polysaccharide processing has been designed and refined over the years, but a lack of comprehensive valorisation of lignin has been noted. Biomass delignification processes should expose cellulose fibres intact (pulp and paper activity) or accessible to enzymes (biotechnological industry), but simultaneously produce high-quality lignin with chemical and structural features as close as possible to native. Low molecular dispersion and high degree of functional groups, including hydroxyl and carboxylic groups, are desired for the fractionated lignin. Functional and less condensed lignin will be more prone for chemical reaction either in its cleavage to value added monomeric aromatic compounds [10] or in the synthesis of new bio-based materials [11]. Therefore, it is reasonable that efforts to develop new biomass fractionation processes are crucial in this research. The main strategy may stand on the priority to isolate polysaccharides with simultaneous separation of high-quality lignin fraction. However, there is also the “lignin-first” approach, where processes aim directly at the isolation/conversion of lignin [12]. A major example of the lignin-first approach is the reductive cleavage fractionation (RCF) technology that comprises solvent-based lignin extraction with integrated conversion in the presence of a transition metal under hydrogen atmosphere or assisted with a hydrogen-donor solvent or another reducing agent [12].

Independently of the main target, polysaccharides or lignin, a sustainable use of lignocellulosic biomass still relies on the adequate valorisation of each macromolecular component. In this regard, efficiency and selectivity on the separation/fractionation of cellulose, hemicellulose and lignin are important criteria to evaluate the sustainability of current and new biomass valorisation processes. Furthermore, the environmental impact of developed technologies must be assessed, where the application of environmentally friendly tools (solvents, catalysts, reagents, etc.) must be encouraged and coupled with low-energy requirements. In this sense, green solvents have rose as key tools to enable biomass fractionation at mild conditions. Ionic liquids (ILs) and deep eutectic solvents (DES) have been elected as major players, especially on the biomass delignification step. The isolated lignin has exhibited interesting physicochemical properties for further application, being one of the advantages of these new technologies against conventional processes mentioned above.

This article briefly reveals some of the ground-breaking scientific achievements in biomass delignification with ILs and DES. The definition and physicochemical properties of these solvents are quite important to be described and distinguished beforehand to understand the mechanistic insights upon their biomass delignification performance. Afterwards, their delignification ability and why isolated lignin discloses favourable properties for further valorisation will be discussed as well.

Ionic liquids *vs* Deep Eutectic Solvents: definition and properties

ILs and DES have been claimed as green solvents and interesting alternatives to traditional solvents. Due to their wide range of physicochemical properties, ILs and DES have been applied in many fields of research, such as chemical catalysis and separation, pharmaceutical and cosmetic formulations, biological applications, CO_2 sequestration, fuel desulfurization, biomass fractionation and conversion, among others. Although ILs and DES possess similar applications and share some characteristics, their differences must be stressed out and clarified, including definition, chemical composition and physicochemical properties.

ILs have been discovered more than 100 years ago, when Paul Walden mixed nitric acid with ethanolamine to obtain ethylammonium nitrate ($[EtNH_3][NO_3]$) with the melting point of 12 °C [13]. Since then, the research on ILs and their applications have been expanded exponentially. By definition, ILs are salts composed of an asymmetric and large organic cation coupled with an inorganic or organic anion, exhibiting a melting point < 100 °C [13]. The low melting point is a consequence of weaker interactions established between ILs’ cation and anion when compared to strong ionic bonds existing in ordinary salts, like sodium chloride, which melts at 801 °C. Furthermore, categorization between protic ionic liquids (PILs) and aprotic ionic liquids (AILs) has been adopted. PILs disclose the advantage of being easier to prepare as their synthesis rely on a simple proton transference from a Brønsted acid to a Brønsted base. In this case, chemical equilibrium between ions and molecular

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precursors are established. The higher the difference between acid and base pka (ΔpKa), the higher is the ionization of PIL. On the other hand, the synthesis of AILs includes different synthetic strategies, as for instance, the Menshutkin reaction that enables the formation of a quaternary positive charged ammonium from neutral amine species. Moreover, AILs possess substituents other than a proton (*e.g.* alkyl group) at the site occupied by the labile proton in analogous PILs.

The existing multiple combinations of cations and anions to make up an IL give them the term of “designer” or “tailor-made” solvents, *i.e.*, an IL can be synthesized for a target application. Some examples of cations and anions that have been used in biomass delignification are given in Figure 1.

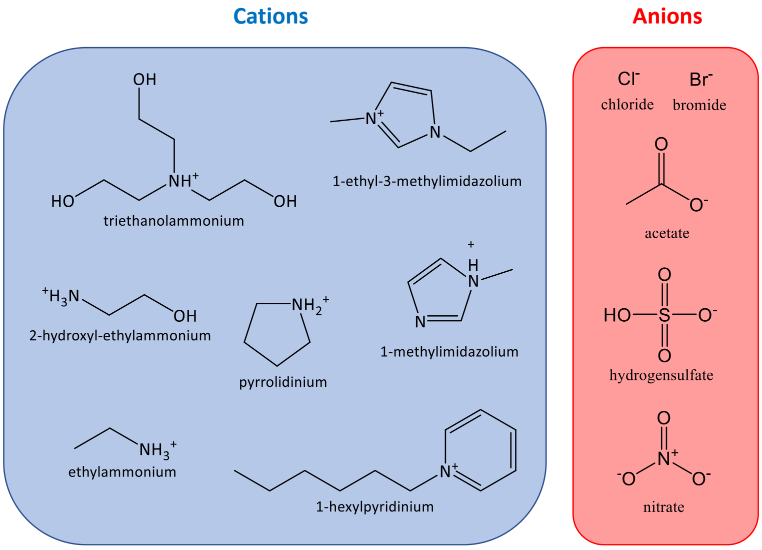

Fig.1. Some examples of cations and anions that make up ionic liquids.

In general, ILs present remarkable features, including negligible vapour pressure, non-flammability, high chemical and thermal stabilities, among others. ILs have been recognized as excellent solvents by taking in account their wide range of polarity, acidity and basicity, which can be tuned by changing the cation or anion in their constitution. Although a definition and general properties can be ascribed to ILs, there are still some exceptions. Some ILs can be volatile, flammable, unstable, and even toxic [14,15]. In this regard, a wise choice of IL must be always considered by having in mind the desired application.

In contrast to ILs, DES appears as “juvenile” solvents, since only in the beginning of the present century Abbott *et al.* have reported them for the first time [16]. Nevertheless, it should be stated that the term eutectic mixture is older. Eutectic mixture refers to the combination of at least two components, generally a hydrogen bond acceptor (HBA) and a hydrogen bond donor (HBD) species, which establish an interaction network (hydrogen bonds and others) capable of decreasing the melting temperature of the mixture (Figure 3 – red line) in comparison with the melting temperature of the individual compounds (Figure 3 – black line as indicative). In other words, a simple mixture of two solids at room temperature may allow the formation of a liquid. An example is given by the solid mixture of urea and a quaternary ammonium salt that turns into a liquid after heating. The addition of the term “deep” to a eutectic mixture relies on a significant deviation of the melting temperature of the mixture (Figure 3 – blue line) when compared to that of an ideal eutectic mixture (Figure 3 – red line). In order to identify the eutectic mixture as “deep or not deep” phase diagrams and thermodynamic calculations must be taken in account as reported elsewhere [17]. Although this distinction is important to understand the physicochemical behaviour of the system, most of the times is irrelevant from the application point of view.

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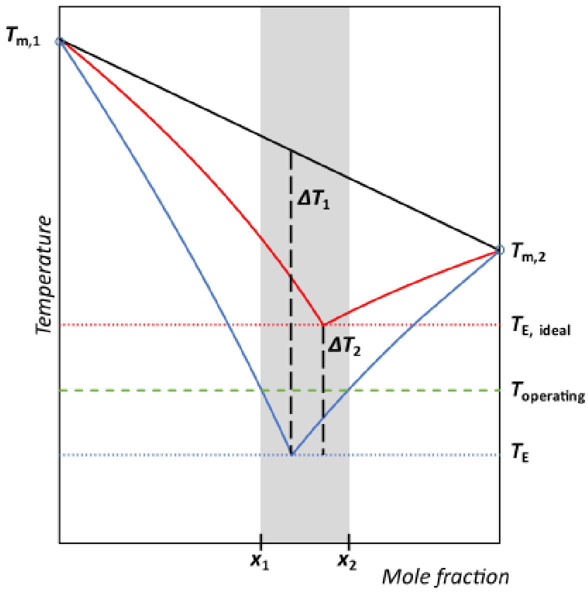

Fig. 2. Schematic representation of solid-liquid equilibria of a simple ideal eutectic mixture (red line) and a deep eutectic mixture (blue line). The black line is just a guide to the eye between melting temperatures of two compounds ($T_{m,1}$ and $T_{m,2}$). $T_{E,\ ideal}$ = eutectic temperature of an ideal eutectic mixture; T_E = eutectic temperature of deep eutectic mixture. Reprinted with permission from *[17]*.

DES (or ES) can be divided into five different categories: Type I and Type II combine a quaternary ammonium salt (usually cholinium chloride – [Ch]Cl) with metal chloride (*e.g.* ZiCl2) or metal chloride hydrate (*e.g.* $FeCl3{\cdot}6H_2O$), respectively; Type III relies on the mixture of a quaternary ammonium salt and a HBD (*e.g.* amides, carboxylic acids, alcohols, among others), which is the most used combination in literature; Type IV is composed of a metal chloride hydrate and HBD; while Type V is a more recent class and comprises the mixture of non-ionic components, i.e., molecular HBAs and HBDs [18,19]. Although hydrogen bonding has been reported as major interaction network existing between DES components (HBA and HBD), and this can be especially true for Type V DES, one should not disregard the ionic bonds in the organic salt(s) composing DES categorized in Types I to IV. There is indeed a distinct chemistry between each DES category and such difference is more relevant when comparing to ILs, which are solely composed of ions (AILs) or mostly composed of ions (PILs). Similar to ILs, the numerous possibilities of combinations to make up DES allow this kind of solvents to be used in a myriad of applications and to be called “designer” or “tailor-made” solvents as well. Some examples of Type III DES components are given in Figure 3. DES share similar features with ILs, including negligible vapour pressure, high chemical and thermal stabilities. Once more, there are exceptions and not all DES exhibit these properties. Moreover, analogous to ILs, a wide range of acidity, basicity, and polarity, among other properties can be tuned by changing DES components and their molar ratios. For this reason, similar applications can be found in literature for both solvents, thus there is quite often the confusion in distinguishing them.

However, there are distinct features that must be highlighted between these two major classes of green solvents. For instance, a comparison of viscosity between two types of most used DES ([Ch]Cl-based) and ILs (imidazolium-based) was performed elsewhere [20]. DES disclosed a higher viscosity range (0.05 Pa·s up to 2.000 Pa·s) than ILs (0.02 Pa·s up to 7 Pa·s). The strong hydrogen bonding between [Ch]Cl and its HBD counterpart was mentioned to have higher influence on viscosity than that of cation-anion pair of imidazolium-based ILs. The high viscosity can be an issue associated to DES for industrial applications, particularly those with high number of hydroxyl groups that establish a strong hydrogen bonding network, like sugar-based and polyol-based DES. Although the problem of the high viscosity can be solved quickly by adding water to the system, an excess of water may lead to the disruption of nanostructure lattice of DES. In the application point of view, this fact can be sometimes irrelevant, but a mixture of two components highly diluted in water may not be reasonable. In cases where water plays a crucial role, a simple aqueous solution of the most influent DES component will be more appropriate. Another relevant aspect to distinguish DES and ILs is the preparation of the solvent. DES has been seen as easier to prepare than ILs, which often need complex synthesis, specially AILs as described before. As simple mixture of pure components, DES do not need further purification steps before use.

Although DES and ILs have been called green solvents mostly because of the negligible vapour pressure, other important environmental factors, such as toxicity and biodegradability, must be addressed as well. Bearing in mind the high number and chemical variability of DES and ILs constituents, it is obvious that these solvents can exhibit high, moderate and low toxicity. Both DES and IL can be toxic depending on the precursor molecules, while sometimes a synergistic effect between components may contribute to higher toxicity than its precursors [21–23] or even lower toxicity [24]. On the other hand, the high stability of these solvents negatively influences its biodegradability. In general, classical imidazolium-based and pyridinium-based ILs are more stable and their biodegradability is difficult. ILs and DES containing natural precursors, like amino acids, sugars, alcohols and organic acids are more biodegradable, thus they could be recommended within an environmental perspective. Furthermore, cholinium-based ILs or [Ch]Cl-based DES are preferred concerning their biodegradability potential. For instance, [Ch]Cl-based DES, such as [Ch]Cl:glycerol (Gly) and [Ch]Cl:oxalic acid (OxA) presented biodegradability yields of 96 % and 68 %, respectively [25], while cholinium-based ILs composed of aminoacids (as anion form) showed also good biodegradability levels (62-87 %) [26]. Nevertheless, in cases where ILs and DES may disclose toxicity and low biodegradability, their full recyclability is of utmost importance, yet a big challenge to surpass. Among several toxicity and biodegradability studies, it is hard to generalize if ILs and DES are non-toxic or biodegradable. There are ILs and DES that present the lowest standards of toxicity and biodegradability, while others exhibit the opposite. Therefore, a case-by-case assessment of the "green" character of these solvents is always required for any chemical process.

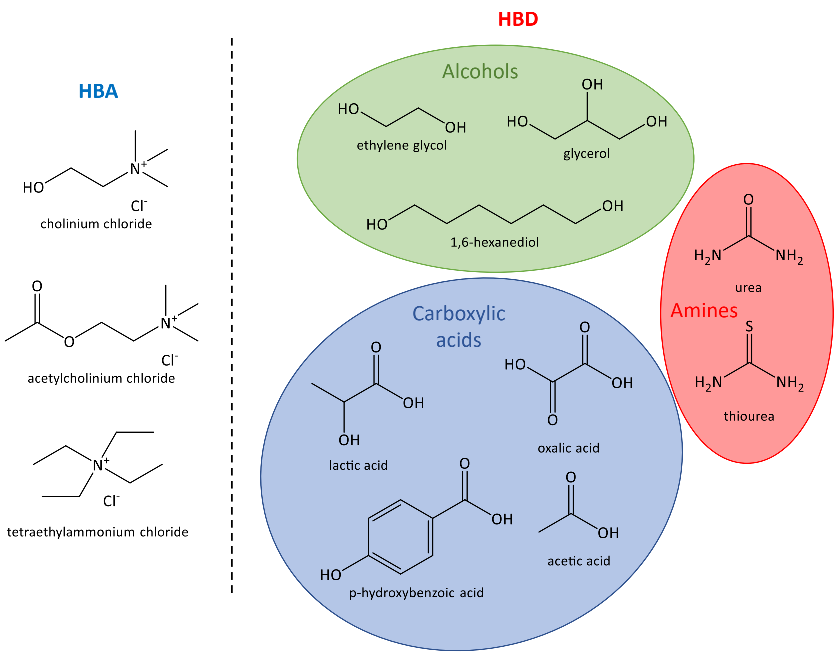

Fig. 3. Some examples of Type III DES possessing a HBA (quaternary ammonium salts) and a HBD (alcohols, carboxylic acids and amines).

Biomass fractionation/delignification with ionic liquids

The application of ILs in lignocellulosic biomass valorisation has slightly more than a decade of research. In 2007, Kilpelainen *et al.* were the first researchers to demonstrate the ability of ILs, in particular imidazolium-based ILs, to fully dissolve wood at mild conditions (< 130 °C) [27]. This work opened the window for a myriad of other studies unveiling the fundamental chemistry behind the IL capacity of interacting with all biomass components and disclosing different strategies for its selective fractionation [28–30]. The mechanisms behind cellulose, hemicellulose and lignin dissolution were mainly ascribed to the ability of ILs to disrupt biomass hydrogen bond matrix and establish new and stronger ones with macromolecular components [31]. In this regard, Remsing *et al.* reported that IL anion has a more relevant role on the disruption and mediation of hydrogen bonds with biomass polysaccharides than IL cation. In another study, Brandt and co-workers examined the Kamlet-Taft solvatochromic parameters of several ILs and correlated them with the capacity of ILs to dissolve biomass [32]. The researchers found that ILs possessing high basicity anions enables swelling and dissolution of biomass efficiently. Two major examples are the imidazolium-based ILs composed of chloride (Cl^-) and acetate (CH_3COO) [33], which among several types of ILs demonstrated the best performance to achieve whole biomass dissolution.

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After biomass dissolution in ILs, the precipitation and regeneration of biomass components can be assisted by the addition of anti-solvents. For instance, cellulose can be regenerated by diluting IL/biomass mixture with water. Basically, water molecules make a hydrodynamic shell around IL ions hindering their interaction with cellulose fibres, which are insoluble in water [33]. This clearly enables the separation of cellulose from other biomass fractions, such as hemicelluloses and lignin. However, the structural characteristics of cellulose suffer a drastic change after regeneration, *i.e.*, the initial semi-crystalline structure shifts to an amorphous-like pulp in the regenerated form. This phenomenon is a technological advantage when targeting the enzymatic digestibility towards glucose by giving more accessible sites to enzymes. However, it is the opposite for paper making, since cellulose loses the desired mechanical properties of their crystalline and well-organized fibres. After cellulose regeneration, hemicelluloses can be precipitated by the addition of ethanol to the resulting liquid medium, while a lignin solid fraction is later obtained by acidification as described elsewhere [30,34]. This selective precipitation and separation of main biomass fractions in a three-step process is one of the advantages of IL technology when benchmarking with conventional fractionation technologies.

As mentioned before, imidazolium-based ILs containing Cl^- or CH_3COO^- were the most efficient enabling biomass dissolution and further selective precipitation of macromolecular components. However, different works reported that some covalent interactions between imidazolium cation (at C2 position) with cellulose or even degradation into volatile neutral species during the dissolution process may occur leading to IL mass losses in the end of the process [35,36]. The fact imidazolium-based ILs are not cheap leads to a negative impact on the total cost of the process. Furthermore, regeneration and reuse of this kind of ILs revealed slight losses of the dissolution performance, caused by biomass components that remain dissolved in the regenerated solvent. Although imidazolium-based ILs and other AILs capable of dissolving whole biomass have shown efficiency towards biomass fractionation, their high price alongside with mass loss has led to some reluctance among scientific and industry communities to apply them in industrial processes. Furthermore, the use of high amount of water to regenerate and wash cellulose-rich samples can be considered an economic disadvantage.

Therefore, other types of ILs were investigated and those that exhibited more acceptance of application have been PILs, since they are less costly and easier to synthesize than AILs. As mentioned before PILs are synthesised through simple acid-base chemistry between the reaction of a Brønsted acid and a Brønsted base. Acetic, propionic, hexanoic acids are examples of Brønsted acid precursors, while pyridine, pyrrolidine and tertiary amines are examples of Brønsted base precursors used in PIL synthesis. The physicochemical properties of PILs allow different behaviour on the interaction with biomass components in contrast to AILs. A technical advantage of PILs is their ability towards the selective biomass delignification, or in other words, lignin extraction and dissolution from biomass without dissolving cellulose. This selectivity for lignin has enabled multiple studies with PILs on biomass fractionation as well.

In 2014, Achinivu *et al.* were the first to demonstrate biomass delignification with PILs, namely pyridinium-based ILs [37]. The researchers obtained approximately 70 wt% lignin extraction from corn stover after treatment with pyrrolidinium acetate ([Pyrr][CH_3COO]) at 90 °C for 24 h. Among examined cations, pyrrolidinium revealed better performance than pyridinium and imidazolium cations in presence of the counter anion acetate [37]. The use of 2-hydroxyl-ethylammonium (HEA) in combination with acetate also exhibited good performances on lignin extraction after treatment of cashew apple bagasse [38] and sugarcane bagasse [39].These studies revealed that the presence of acetate as the PIL anion showed good performance to enable high biomass delignification yields. Nevertheless, high residence time or high temperature is needed to afford those results.

In a different perspective, Hallett and coworkers demonstrated hydrogen sulfate (HSO_4)-based PILs as both cheap and efficient solvents for biomass delignification. The authors have claimed that mixing sulfuric acid with alkyl amines (*e.g.* triethylamine or *N*,*N*-dimethylbutylamine) or alkylalcohol amines (*e.g.* ethanolamine or triethanolamine) allow simple synthesis of PILs reaching a total price around $\$1 \cdot Kg^{-1}$ and reducing the overall costs of the biomass delignification process [40]. These kind of ILs are able to induce biomass delignification (85 %) at mild conditions (120°C) [40]. The success of implementing cheap triethylammonium hydrogensulfate ([TEA][HSO_4]) for biomass delignification have also led to the launch of Lixea Ltd. a start-up company that is now running a pilot scale plant to process waste wood, agricultural by-products and sustainably grown biomass with this low cost solvent towards the valorisation of both polysaccharide and lignin fractions into value added compounds [41] The efficiency of HSO_4-based ILs on biomass delignification was prior shown by Cox and co-authors, who demonstrated the effective cleavage of β-O-4 bonds in lignin model compounds by this kind of ILs.

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Similar findings were observed with Cl-based PILs, including 1-methylimidazolium chloride [Hmim][Cl] [42], 1-ethylimidazolium chloride [Heim][Cl] [43], 1-hexylpyridinium chloride ([Hpy][Cl]) [44], synthesised through the mixture of hydrochloric acid and corresponding amines.

The fact some PILs can be distilled in the end of the process was pointed out as technical advantage against AILs. The application of heat and vacuum enables the dissociation of the acid−base pair to molecular acid and base precursors, which are then distilled as azeotropes. In the end, the ionicity returns to the regenerated solvent through condensation at low temperature. After biomass delignification, [TEA][HSO_4] can be recovered by distillation up to 99% [40], while 93 % recovery of [Heim][Cl] was achieved elsewhere [43]. However, this regenerative distillation of PILs cannot be seen as energetically and economically favourable, especially when increasing the scale to biomass tonnes. Indeed, the IL regeneration by precipitation/extraction of dissolved biomass components and further evaporation of anti-solvents, such as water, ethanol and acetone, still continue to be the right decision to do it.

Regarding the quality of isolated lignin after biomass delignification with ILs, the opinions of researchers diverge. In fact, comprehensive data regarding the mechanisms and structural modifications of lignin during biomass dissolution by AILs or biomass delignification with PILs is lacking. Few works however have been unveiling the effects of ILs on lignin structure and overall quality of isolated fraction. Isolated lignin from biomass treatment with 1-ethyl-3-methylimidazolium acetate ([emim][CH_3COO]) is one of the most studied lignins [45–47]. It is characterised by low chemical and structural modification in contrast to native lignin, although dependent on the severity of biomass treatment. For mild conditions (<120 °C), relatively moderate molecular weight (MW) can be achieved (*e.g.* 6347 $g \cdot mol^{-1}$) with narrow polydispersity (PDI <2) [46]. Furthermore, a decrease of the aliphatic OH content alongside with an increase of phenolic OH content is generally observed as consequence of dehydration of lignin unit aliphatic chains and β-O-4 ether bond cleavage, respectively [48]. On the other hand, it seems that C-C bonds, like β-β and β-5, are preserved at mild conditions, while at high temperatures (*e.g.* 160 °C) this kind of linkages increase due to repolymerization reactions [47]. Other chemical changes in lignin structure, such as demethylation, can be induced by [emim][CH_3COO] [48]. All these changes in the isolated lignin seem unanimous in literature when using this IL, yet the mechanisms behind those reactions are still not clear. In addition, it is important to highlight that isolated lignin with [emim][CH_3COO] may not be free of xylan impurities as shown in the 2D HSQC spectrum reported elsewhere [47].

On the other hand, the analysis of isolated lignin from biomass delignification with HSO_4-based PILs has shown an efficient disruption of hemicellulose-lignin linkages as well as β-O-4 ether bond cleavage. This is a consequence of the acidic media provided by these ILs [49]. The 2D HSQC spectrum of isolated lignin confirms the absence of β-O-4 signals as well as xylan and cellulose chemical shifts [50]. Researchers have also found that this type of ILs are able to cleave ether bonds existing in lignin subunits containing β–β and β-5 linkages, decreasing their intensity in 2D HSQC spectra [50]. The acidity of HSO_4-based PILs also enables the isolation of low MW lignins when compared [emim][CH_3COO]. At long treatments and high temperatures, condensation reactions prevail and substitution reactions on lignin aromatic rings may also occur [50], which must be avoided. However, one important aspect that has not been studied and discussed when using HSO_4-based ILs in biomass delignification is the sulfur contamination in isolated lignin fractions. The isolated lignin must be sulfur-free otherwise no technical advantage will be presented against conventional technologies, like Kraft and Sulfite processes.

<u>Biomass delignification with deep eutectic solvents</u>

The application of DES in biomass fractionation is even more recent. In 2012, the first studies have shown the ability of DES composed of carboxylic acids and [Ch]Cl or aminoacids to dissolve technical lignins [51]. Lignin was dissolved in most of the screened DES, and among them, [Ch]Cl:lactic acid (LA) at molar ratio 1:9 disclosed the highest dissolution performance. In contrast, a high number of DES were examined for cellulose dissolution trials, but the results demonstrated a simple answer: DES are not able to dissolve cellulose [51]. This selectivity for lignin dissolution called the attention of academia and industry, especially the pulp and paper sector, regarding the potential of DES towards selective biomass delignification. In this regard, the Confederation of European Paper Industries (CEPI) chosen deep eutectic solvents (DES) as promising alternative technology to perform a sustainable wood delignification in the future [52]. Since then, several research works dealing with wood and other lignocellulosic biomass delignification processes have been reported [53–57].

Although lignin dissolution trials give some perspectives about the required physicochemical properties of DES to perform biomass delignification, their capacity to disrupt the biomass intricate matrix is crucial. For example, the ability of alcohol-based DES, such as [Ch]Cl:glycerol and [Ch]Cl:ethylene glycol, to dissolve high amount of lignin was manifested elsewhere [58]. However, their capacity to extract lignin from biomass is moderate to low. In literature, there are satisfactory biomass delignification yields using these solvents (71-88%), but this is mostly ascribed to low recalcitrance of studied lignocellulosic materials, such as corncob [54]. For high recalcitrant biomass (*e.g.* wood) the delignification yields are often lower than 50 %. Therefore, these neutral DES disclose low performance to open up the biomass interlinkages and to penetrate and interact efficiently with lignin macromolecules. Similar behaviour is shared by other neutral DES, such as [Ch]Cl:urea (U) [59]. On the other hand, the addition of an acid catalyst (*e.g.* 0.9 % H_2SO_4) to alcohol-based DES offers the ability to react with biomass components increasing significantly the delignification yield (up to 80% after *Miscanthus* biomass treatment [55]).

In contrast, acid-based DES, including [Ch]Cl:LA or [Ch]Cl:oxalic acid (OxA), not only are effective in dissolving technical lignins but also promote biomass delignification efficiently. The acidity of these solvents is key for the disruption of biomass matrix and cleavage of lignin chemical bonds, particularly β-O-4 ether bonds, enabling the selective separation of lignin from cellulose fibres. For instance, [Ch]Cl:LA demontrated the highest selectivity for wood delignification by extracting 62 to 84 % of the initial lignin in wood at 130 or 145 °C for 6 h. Alvarez-Vasco *et al.* interrelated the selectivity for delignification mediated by [Ch]Cl:LA with its ability to cleave β-O-4 ether bonds [56]. Similar to ILs, few studies have addressed the mechanisms behind the interaction and capacity of DES for biomass delignification. Particularly noteworthy, LA:[Ch]Cl revealed a superior delignification than pure lactic acid, suggesting a positive role of [Ch]Cl in this process event at low content [60]. It was further demonstrated than in case of acidic [Ch]Cl-based DES the cleavage of β-O-4 ether bonds is boosted by the presence of the chloride anion [61]. A nucleophile substitution of neighbour hydroxyl groups of β-O-4 linkages by chloride anion and its subsequent leaving enables a fast formation of enol-ether intermediate that enhances the cleavage [61]. Contrasting to ILs, acid-based DES maintain the integrity of the crystalline structure of cellulose fibres after delignification process, although fibre length is reduced as consequence of acid hydrolysis of cellulose amorphous sections. In this sense, the obtained cellulose fibres reveal lower mechanical performance to produce high quality paper, but it may offer an alternative for other product grades, such as dissolving pulp towards viscose applications.

Although DES have been demonstrated potential for biomass delignification, the viscosity of a large number of DES can be considered as disadvantage as mentioned above. A simple solution comes with the addition of water to reduce the mass transfer limitations. While for some studies the addition of water improved biomass delignification [53], others revealed no change in DES performance (at low water contents) [62]. These differences can be explained by distinct behaviours in the solvation of lignin mediated by DES in presence of water. DES may act as co-solvents, or as hydrotropes enhancing lignin dissolution in aqueous systems significantly [63,64]. A good example is [Ch]Cl:1,6-hexanediol that is capable of maintaining maximal Kraft lignin solubility up to 50 wt% water contents. These results are quite relevant since Kraft lignin solubility in water is negligible. There also cases where the hydrotropic effect exhibited by DES enabled a significant improvement of lignin solubility in aqueous solution when compared to pristine DES [64]. Basically, the presence of hydrophilic water molecules allows stronger interaction between the most hydrophobic regions between lignin and DES [65]. The hydrophobic interactions of both DES and lignin with water are weaker than water-water hydrogen bonds, resulting in strong agglomeration of hydrotropic DES around lignin macromolecules [65]. Recently, the addition of water enhanced the performance of DES in wood delignification, due to the reduction of mass transfer limitations, but also to this hydrotropic mechanism [66].

Another strategy towards biomass delignification is the use of aromatic-based DES. Kim and co-workers demonstrated the ability of DES constituted by lignin derived phenolic compounds, such as catechol, vanillin, *p*-coumaric acid or *p*-hydroxybenzoic acid for biomass delignification [62,67]. One of advantages is the strong π-π interactions between aromatic rings of solvent and lignin macromolecules favouring lignin extraction from biomass. Up to 70 % lignin removal from woody biomass was achieved with [Ch]Cl:*p*-hydroxybenzoic acid [67]. Although a clear message of sustainability and potential closed-loop biorefinery concept was disclosed by this kind of strategy, the separation of lignin from such solvents is not efficient and leads to significant reduction of DES performance from first use to following recycle runs [67].

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After biomass delignification, lignin can be easily precipitated from DES liquid stream through the addition of water, which plays as lignin anti-solvent [56]. This precipitation process is more efficient when using acid-based DES. The dilution of this type of DES allows the formation of an aqueous solution with low pH enhancing the flocculation of previous extracted lignin macromolecules. For neutral DES, acidic water is needed to reach similar precipitation yields. The precipitated lignin has been characterised by different spectroscopic techniques and often highlighted as a high-quality fraction. The selective cleavage of β-O-4 ether bonds allows an increase of phenolic hydroxyl groups, which means high reactivity properties exhibited by the isolated lignin. Tan *et al.* studied the variation of phenolic hydroxyl groups of isolated lignins with DES containing different organic acids (*e.g.* formic, acetic, propionic, lactic, malic, citric, maleic acids, among others) [68]. Among them, [Ch]Cl:LA disclosed the highest yield of phenolic hydroxyl groups in lignin structure and was more efficient than pure lactic acid. Therefore, [Ch]Cl seems important not only to speed up the delignification process but also it may offer higher stability to phenolic hydroxyl groups limiting condensation reactions between lignin macromolecules. Moreover, the cleavage of β-O-4 ether bonds also enables a decrease of the molecular weight in contrast to native lignins. High purity, ranging from 85 wt.% to 95 wt.%, has been reported for these DES extracted lignins and their use in further applications have been recommended. In addition, these lignins are generally sulphur- and carbohydrate-free and show low condensation degree and homogeneous molecular size distribution [53,56,57]. These are desired characteristics to enable transformation of lignin in new products and materials. It is unquestionable that the presence of [Ch]Cl is significant for delignification efficiency and final characteristics of isolated lignin, thus more in-depth research is needed to unveil the mechanisms behind this delignification and to show the importance of the halide salt/organic acid mixture instead pure or aqueous solution of organic acid (organosolv).

Impact

The development of novel and innovative processes towards efficient fractionation of lignocellulosic biomass is highly desirable and brings tremendous impact at social, economic and environmental levels. The possibility to produce goods and commodities that we daily know from renewable resources like biomass is expected to progress the sustainability and well fair of world population by disconnecting society from the excessive dependence on pollutant fossil-based resources. On the other hand, the full exploitation of biomass towards energy, fuels, materials and other bio-based products will boost all potentialities of the bioeconomy agenda. This will be achieved when a cascade of fractionation/conversion activities are well designed allowing continuous commercialization of those products. Technical gaps and limitations are still hindering this reality and one of the common drawbacks remains on the disruption of biomass intricate matrix.

The academia and industry have been focused on developing cheap and efficient processes for biomass fractionation, although a duly attention has not been given to selectivity. The selectivity is a crucial aspect that must be optimised to get the full potential of biomass components, namely cellulose, hemicellulose and lignin. A major example lies on biomass delignification step that must address totally or at least a good balance between three important outputs: i) high delignification yield; ii) maintain lignin chemical and structural properties close to native; and iii) avoid degradation of polysaccharides. The existing biomass processing technologies may fail at least one of these outputs. In this sense, the use of tailor-made solvents like ILs and DES with selected physicochemical properties may stand as excellent alternatives. In the last decades of research, they have been showing potential for cheap, effective and sustainable biomass delignification and produce high quality lignin for further conversion and valorisation. Furthermore, not only their performance must be highlighted, but also their eco-friendly benefits. Biomass fractionation and conversion technologies must comprise green chemistry and environmentally friendly practices otherwise no real leverage is gained over conventional petrochemistry activity. In fact, there is a clear advantage in implementing technologies with green solvents to increase process sustainability and to reduce the negative impacts of biomass processing on the environment. ILs and DES have been connoted as such, yet their environmental impact, mostly measured by their toxicity and biodegradability, must be evaluated case-by-case. Moreover, in cases where the technological use of these solvents outperforms any other biomass processing technology, but there will be constraints regarding their toxicity and biodegradability, the full recyclability of the solvent is imperative. There are few studies reporting the recovery of these solvents, although this is a bottleneck that needs much more efforts in research to improve the development and implementation of these technologies in industry.

Therefore, incentives for green chemistry innovations on biomass valorisation must be given, where ILs and DES may play important roles in the future. Among them, ILs are now on the front row to be the next technology for biomass fractionation and, as mentioned before, Lixea Ltd. is the first start-up company addressing it. Yet, more incentives are needed to push start-ups and large companies for betting on IL technologies. In case of DES, since limited data is available, more investment in research projects is required to fully understand their potential for biomass fractionation, from fundamentals to application.

Conclusions

Biomass fractionation should move to another level of development where selectivity must be an important criterion alongside with both performance and ecological efficiencies. In this respect, more selective processes are expected to play an important role to expose cellulose, hemicellulose and lignin fractions separately allowing cascade exploitation of biomass into desired products. This means that the same or higher attention must be given to lignin valorisation as it has been done to polysaccharides, particularly to cellulose. The aromatic character of lignin makes it a potential renewable source of new materials and products, replacing the overexploited aromatic fraction of non-renewable crude oil. In this sense, selective biomass delignification processes are highly required to go beyond the suboptimal use of biomass in conventional processes currently running on bio-based industries, such as pulp and paper industry and 2G ethanol companies, towards biorefineries.

In this sense, the application of ILs and DES in biomass delignification have been disclosing promising results by enabling higher delignification yields, higher lignin purity and less polysaccharide degradation in comparison to conventional methods. Particularly, AILs disclose the capacity of dissolving whole biomass to enable further precipitation of major components and subsequent lignin isolation, while both PILs and DES show higher selectivity for lignin extraction and isolation leaving a polysaccharide-rich solid. In general, mild conditions are applied to biomass with these solvents allowing the isolation of lignin fractions with low and narrow molecular weights, low chemical structure modification and free of carbohydrate and sulfur contents. These are relevant physicochemical features that lignin must exhibit for further conversion into chemicals and materials. Yet, more data regarding full chemical and analytical characterisation of isolated lignins, which includes NMR techniques (HSQC, HMBC, ^{13}C NMR and ^{31}P NMR), GPC, FT-IR, TGA and py-GC/MS analysis, is needed for fair comparison and to address standardization of lignin quality.

Although ILs and DES share similar properties, they also exhibit some differences with significant impact on delignification performance, environmental footprint (toxicity and biodegradability) and solvent recyclability. This makes difficult any kind of generalization to these solvents, thus case-by-case studies must be always assessed. There are still mechanistic insights that need to be unfolded with more in-depth research, while more studies benchmarking biomass delignification using ILs and DES with similar molecular composition are required.

Conflict of interest

There are no conflicts to declare.

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CALCULATION OF SUSTAINABLE DEVELOPMENT INDEX IN THE EU AND UKRAINE

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Abstract
It is proposed using certain indicators to assess the sustainable development of the EU countries and Ukraine: for the economic measuring - the global competitiveness index, the global innovation index and the index of economic freedom; for the social measuring - the social progress index, the human development index, quality of life index; for the environmental measuring - environmental performance index. The analysis of each selected indices of the EU countries and Ukraine is carried out. The methodology for calculating the ratio of the economic, social and environmental components of sustainable development for each EU country and Ukraine is presented. Attention is focused on the significant regional diversification of sustainable development and its components in the EU countries and Ukraine; the highest, middle and lowest levels of sustainable development of counties are identified.
Impact: the methodology for the study of sustainable development, proposed by the authors on the example of the EU countries and Ukraine, is based on objective international ratings that have a transparent calculation methodology. These international ratings are constantly updated and cover most of the countries of the world. Therefore, the proposed methodology makes it possible to identify countries with the highest level of economic, social and environmental development; calculate the index of sustainable development of any country in the world.

Keywords
sustainable development Index, European Union and Ukraine, calculation methodology, sustainable development indicators

Introduction

In modern conditions, more and more doubts are being placed on the expediency of development, in the centre of which is the material production. This necessitates a change in the entire paradigm - from the ideology of accumulating material wealth on earth to the ideology of "reasonable sufficiency", from the ideology of competition

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to the mutual assistance one. Approaches to sustainable development are constantly being improved in the countries of the European Union, therefore, it is expedient to study methodologies and indicators for assessing sustainable development, which determines the relevance of the study.

The scientific works of many researchers are devoted to the study of sustainable development processes. In particular, in the works of G. H. Brundtland [1], the use of the term "sustainable development" and the concept of sustainable development of the world was first proposed. A number of scientists at the end of the twentieth century investigated the compliance of the modern economy with the rules of a stable state [2], the need to implement a global policy on sustainable consumption and production [3], global problems associated with modeling the growth of the planet's population and the simultaneous depletion of natural resources [4], historical background ideas of sustainable development [5], the prospects of modeling scientific policy to provide global information to human society, finding out the possibilities for coordinating policies between countries in order to achieve sustainable development of the world economy in the context of the constraints of the global environment [6].

Modern works are devoted to interaction of many aspects of the social, economic and environmental component and sustainable development of society. Some of them disclose methods of air transport safety integration in the mechanism of interaction between sustainable development goals and sustainable development safety management through managerial, functional and informational links between sustainable development subsystems and various hierarchical safety levels [7]. The work of N. Dalevska, V. Khobta, A. Kwilinski, S. Kravchenko [8] proposes a methodology and tools of economic and mathematical modeling to assess the level of international trade development and investment relations, the life expectancy, the standard of living and prosperity of international entities under the influence of sources of economic growth in the context of sustainable development. Researchers of Sumy State University Ukraine consider the impact of macroeconomic stability on improving the energy efficiency of countries [9], and assesses the growth of competitiveness in the world market during the reorientation from a traditional to a sustainable business model [10]. Sustainable business models draw attention to a long-term business perspective, which takes into account both evolutionary changes in the economic, technological, environmental and social dimensions, but also changes that occur suddenly and radically impact the economic eco-systems.

The ecological aspects of sustainable development are considered in work [11]. It is said that the formation and use of waste is one of the main problems of civilization, and the implementation of sustainable development concept goals is one of the solutions to this issue. In work [12] attention is focused on assessing the impact of climate change and environmental sustainability of the modern world.

The work [13] is devoted to the analysis of the structure and dynamics of scientific publications in the field of environmental management and social marketing in their interconnection. The proceeding [14] focuses on the search for systemic solutions to multidisciplinary problems of the international economy and globalization in the context of innovative development, information technology and sustainable development.

The work [15] views the patterns of development of open stationary systems on the example of processes and phenomena in nature and society, as well as the interconnection between the energy and information characteristics of transformation processes. It also analyzes the concept of "sustainable development of socio-economic systems", basic principles, methods and tools for ensuring sustainable development of social systems. Researchers [16,17] attempted to assess the sustainable development of the country using the index method.

Works of 2020 [18,19] are related to the sustainable development of the global health system and its transformation to stable state, given the COVID-19 pandemic.

At the same time, the transition to an information society leads to a change in the structure of total capital in favour of human capital, increasing the intangible flows of finance, information and intellectual property. These flows have already exceed the volume of movement of tangible goods by seven times [20]. The development of a new, "weightless" economy is stimulated not only by a shortage of natural resources and care of the natural environment, but also by an increase in the volume of information and knowledge, acquiring the value of a demanded product.

From the environmental point of view, sustainable development should ensure the integrity of biological and physical natural systems, their viability. The global stability of the entire biosphere depends on this. As a result of insufficient monitoring of the impact of climate change and postponed preventive actions, are environmental disasters, which affect the economic development and living conditions for people. This situation is observed especially in the countries of the global south, e.g. in Brazil [21].

The ability to assess the environmental, economic and social threats properly is of particular importance. The tools like a novel approach to the Sustainable Development Index calculation can help to measure the progress of realization of sustainable development goals in many different areas of industrial activity. SDI as well as the Life Cycle Assessment tools should be continuously developed [22,23].

Methods

Theory and practice have shown that at the turn of the century V. Vernadsky's teaching about the noosphere turned out to be a necessary platform for developing a triune concept of sustainable ecological, socio-economic development. The generalization of this concept was made by the United Nations world summits in 1992 and 2002, with the participation of more than 180 countries of the world, many international organizations and leading scientists. Thus, the new concept systematically combined the three main components of sustainable development of society: economic, environmental and social.

The economic approach consists in the optimal use of limited resources and the use of nature-, energy- and material-saving technologies to create a flow of aggregate income, which would ensure at least the conservation (not decrease) of the aggregate capital (physical natural or human), with the use of which this aggregate income is created. The social component is focused on the development of society, on maintaining the stability of social and cultural systems, on reducing the number of conflicts in society. From the ecology point of view, sustainable development should ensure the integrity of biological and physical natural systems, their viability. The global stability of the entire biosphere depends on this. The ability of such systems to self-renew and adapt to various changes is of particular importance, instead of being preserved in a certain static state or degradation and loss of biological diversity.

Systematically harmonization and balancing of these three components is a challenge, especially in time of the global economy transition caused by COVID-19. In particular, the interconnection of social and environmental components leads to necessity of preserving the same rights of use natural resources by today's and future generations. The interaction of social and economic components requires the achievement of justice in the distribution of material wealth between people and the provision of targeted assistance to the relevant strata of society. And, finally, the interaction between the environmental and economic components requires an assessment of the man-made impacts cost on the environment. Solving these problems is the main our time challenge for national governments, authoritative international organizations, etc.

According to the proposed methodology, the economic component is the resulting index of the country's score according to The Global Competitiveness Index, Global Innovation Index and Index of Economic Freedom. Social component is the resulting index of the country's score according to The Social Progress Index, Human Development Index and Quality of life index. Environmental component is the resulting index of the country score according to the Environmental Performance Index. If the study requires, these components can be replaced with another ones.

Calculation algorithm:

1. the average indicator calculation for each of the ratings;
2. the score standardization of each country in the rating by dividing the rating score by the average for the rating;
3. calculation of the economic component from standardised indicators for each country according to the methodology for calculating the integral human development index:

(1) $$\text{Economic component} = \sqrt[3]{\text{GCI} \times \text{GII} \times \text{IEF}}$$

where GCI - is a standardised indicator according to The Global Competitiveness Index, GII - is a standardised indicator according to the Global Innovation Index, IEF - is a standardised indicator according to the Index of Economic Freedom.

4. calculation of the social component from standardised indicators for each country according to the methodology for calculating the integral human development index:

(2) $$\text{Social component} = \sqrt[3]{\text{SPI} \times \text{HDI} \times \text{QLI}}$$

where SPI - is a standardised indicator for The Social Progress Index, HDI is the standardised indicator for the Human.

Development Index, QLI is the standardised indicator for the Quality of Life Index.

5. the environmental component standardization by dividing the rating score by the rating average;
6. the index of sustainable development calculation of the world countries with using of index method and method for calculating the integral index of human development, adapted to the indicators of sustainable development is proposed, namely:

(3) $$SDI = \sqrt[3]{\text{Economic component} \times \text{Social component} \times \text{Environmental componen}t}$$

where SDI – Sustainable Development Index.

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Results and discussion

Sustainable development is a system of mutually agreed management, economic, social, environmental protection measures aimed at forming a system of public relations based on the principles of trust, partnership, solidarity, consensus, ethical values, a safe environment, and national sources of spirituality. Among the main components that ensure sustainable development are the following:

- economic - involves the formation of an economic system harmonised with ecological and social factors of development;
- social - confirms the human rights to a high standard of living in conditions of environmental safety and well-being, that has become one of the important signs of social protection;
- environmental - defines the conditions and boundaries of the restoration of ecological systems as a result of their operation.

The formation of indicators system for quantitative and qualitative assessment of this multidimensional process is an important problem on the way of implementing of sustainable development concept.

The article proposes the novel approach to the Sustainable Development Index calculation. The multidimensional sustainable development index and for the countries of the European Union and Ukraine according to above described methodology.

1. The economic measuring of sustainable development is determined on the basis of three global indicators:
   The first is the Global Competitiveness Index, developed by the organisers of the World Economic Forum and published in the form of the so-called "Global Competitiveness Report". The competitiveness index is formed from three following components: the indicator of the macroeconomic environment (basic requirements), the indicator of the country's technological development (innovation factors) and the indicator of "factors that enhance production" (efficiency enhancers). In turn, these three indicators are calculated basing on the use of 9 data sets of macroeconomic indicators, the level of infrastructure development, the health status of the population and its level of education, the technological readiness of the economy, the level of market efficiency, etc.
   The EU countries and Ukraine have different levels of competitiveness [24], that is shown in Table 1.

Table 1. Global Competitiveness Index of EU countries and Ukraine. *Source: the study based on GCI WEF 2019*

No.	Economy	GCI WEF	No.	Economy	GCI WEF
1	Austria	76.609131	15	Ireland	75.116213
2	Belgium	76.380122	16	Italy	71.528281
3	Bulgaria	64.895011	17	Lithuania	68.351613
4	Cyprus	66.385446	18	Luxembourg	77.028126
5	Czech Republic	70.852799	19	Latvia	66.980444
6	Germany	81.796537	20	Malta	68.546119
7	Greece	62.58073	21	Netherlands	82.39217
8	Denmark	81.174898	22	Poland	68.893312
9	Spain	75.279405	23	Portugal	70.44752
10	Estonia	70.90714	24	Romania	64.355621
11	Finland	80.24563	25	Slovak Republic	66.772277
12	France	78.80624	26	Slovenia	70.200786
13	Croatia	61.938131	27	Sweden	81.247188
14	Hungary	65.075071	28	Ukraine	56.992175

As it can be seen, all EU countries, despite a certain diversity, are included in the first half of the ranking (Greece and Croatia have the worst competitiveness).

Although the leading European countries are constantly increasing their competitiveness in almost all areas, there is also a wide differentiation in terms of the components of competitiveness. The average EU indexes are the lowest in terms of innovation performance. The countries are clearly divided, with a significant gap between the innovation scores for Northern and Western Europe compared to Central, Eastern and Southern Europe. Accelerating the development of the innovative component is crucial for maintaining the current level of well-being, and EU countries can expect a high return of investment in this particular component.

The second is the Global Innovation Index, compiled by the World Intellectual Property Organization, Cornell University

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and «Insead» International Business School. The research has been conducted since 2007. The research is under government control and is aimed at studying economic processes and is annually carried out. The Global Innovation Index is composed by 82 different variables that characterise the innovative development of countries around the world at different levels of economic development in detail.
The EU countries and Ukraine have different levels of innovative development [25], that is shown in Table 2.

Table 2. Global Innovation Index of the EU and Ukraine. *Source: the study based on GII 2019*

No.	Economy	GII	No.	Economy	GII
1	Austria	50.94	15	Ireland	56.10
2	Belgium	50.18	16	Italy	46.30
3	Bulgaria	40.35	17	Lithuania	41.46
4	Cyprus	48.34	18	Luxembourg	53.47
5	Czech Republic	49.43	19	Latvia	43.23
6	Germany	58.19	20	Malta	49.01
7	Greece	38.90	21	Netherlands	61.44
8	Denmark	58.44	22	Poland	41.31
9	Spain	47.85	23	Portugal	44.65
10	Estonia	49.97	24	Romania	36.76
11	Finland	59.83	25	Slovak Republic	42.05
12	France	54.25	26	Slovenia	45.25
13	Croatia	37.82	27	Sweden	63.65
14	Hungary	44.51	28	Ukraine	37.40

Table 2. shows, that the EU countries have significant differences in the innovative component development of their economies. The Netherlands, Sweden, Finland have the highest innovative development, the lowest - Greece, Croatia, Romania).
The third is the Index of Economic Freedom (IEF), created by the intellectual center "Heritage Foundation". The IEF consists of 12 indicators (economic freedoms): 1) freedom of business activity (Business Freedom) 2) transparency of the country's trade policy (Trade Freedom) 3) fiscal policy of the government (Fiscal Freedom) 4) government regulatory policy (Freedom from Government) 5) monetary policy (Monetary Freedom) 6) attracting capital and foreign investment (Investment Freedom) 7) freedom of banking and financial activities (Financial Freedom) 8) observance of private property rights (Property Rights) 9) ensuring labor rights and freedoms (Labor Freedom) 10) efficiency of judicial activity (Judicial Effectiveness) 11) tax burden (Tax Burden) 12) government spending (Gov't Spending).
These twelve indicators are defined from 50 diverse sets of economic, financial, legislative and administrative data.
Economic freedom is the fundamental right of every person to manage their own labor and property. In economically free societies, individuals are free to choose jobs, goods production, spendings and investments in any way they want. All these freedoms are supported and protected by the state. In economically free societies, government also allows free moving of labor, capital, and goods. Government refrains from coercion and pressure on freedoms, intervenes only if it is necessary to preserve and function itself.
Table 3 shows the EU countries and Ukraine Index of Economic Freedom [26].
The weight of each of the 112 factors is considered in the same way, so the general index is the arithmetic mean of the indicators. All countries according to this index are divided into the following groups:

- free, with an indicator of 80-100 (Ireland);
- mostly free, with an indicator of 70-79.9 (these countries are: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Estonia, Finland, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Sweden);
- moderately free, with an indicator of 60-69.9 (these countries are: Greece, Spain, France, Croatia, Hungary, Italy, Poland, Portugal, Romania, Slovakia, Slovenia);
- mostly not free, with an indicator of 50-59.9 (this group includes Ukraine);
- despotic, with an indicator of 0-49.9 (none of the studied countries belongs to this group).

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Table 3. Index of Economic Freedom of the EU countries and Ukraine. *Source: the study based on IEF 2021*

No.	Economy	IEF	No.	Economy	IEF
1	Austria	73.9	15	Ireland	81.4
2	Belgium	70.1	16	Italy	64.9
3	Bulgaria	70.4	17	Lithuania	76.9
4	Cyprus	71.4	18	Luxembourg	76.0
5	Czech Republic	73.8	19	Latvia	72.3
6	Germany	72.5	20	Malta	70.2
7	Greece	60.9	21	Netherlands	76.8
8	Denmark	77.8	22	Poland	69.7
9	Spain	69.9	23	Portugal	67.5
10	Estonia	78.2	24	Romania	69.5
11	Finland	76.1	25	Slovak Republic	68.3
12	France	65.7	26	Slovenia	68.3
13	Croatia	63.6	27	Sweden	74.7
14	Hungary	67.2	28	Ukraine	56.2

2. The social measuring of sustainable development can be formed on the basis of three indicators:
   - the Social Progress Index;
   - the Human Development Index;
   - the Quality of Life Index.

The Social Progress Index is a combined indicator of the international research project The Social Progress Imperative. It measures the achievements of countries around the world in terms of social welfare and social progress. It was developed in 2013 under the leadership of Michael E. Porter, Head of The Social Progress Imperative, Harvard University professor of strategic management and international competitiveness. The Index's editorial board includes representatives from a number of leading universities and research centres, including Harvard Business School and Massachusetts Institute of Technology.
The index does not include economic development indicators of the world countries (such as the level of GDP and GNI), but is intended to assess public welfare in a particular country. Since the study measures social achievement apart from economic indicators, it allows a deeper study of the interconnection between economic and social development.
More than 50 indicators are taken into account in determining the performance of a countries in the field of social progress and combined into three main groups:

- basic human needs - food, access to basic medical care, housing, access to water, electricity and sanitation, the level of personal safety;
- the basics of human well-being - access to basic knowledge and the level of literacy of the population, access to information and means of communication, the level of health care (especially in the context of COVID-19), environmental sustainability;
- human development opportunities - the level of personal and civil freedoms, ensuring human rights and opportunities to make decisions and realise their potential.

The index measures the performance of each country on a scale from 0 (the lowest degree of stability) to 100 (the highest degree of stability) based on the obtained data in three mentioned basic categories. Table 4 shows the data of the Social Progress Index [27] for the studied countries.

As it can be seen from Table 4, countries such as Sweden, the Netherlands, Ireland, Finland, Denmark, Germany have the highest social progress; the lowest - Bulgaria, Romania, Ukraine.

The Human Development Index (HDI) [28] consists of three indicators: population average life expectancy; level of education; country's living standard, which is measured in GDP and PPP, Table 5.

All EU countries (Table 5) according to the HDI belong to countries with a very high level of human development. Ukraine belongs to the group of countries with a high level of human development.

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Table 4. Social Progress Index of the EU countries and Ukraine. *Source: the study based on SPI 2020*

No.	Economy	IEF	No.	Economy	IEF
1	Austria	89.50	15	Ireland	90.35
2	Belgium	89.46	16	Italy	87.36
3	Bulgaria	79.86	17	Lithuania	83.97
4	Cyprus	86.64	18	Luxembourg	89.56
5	Czech Republic	86.69	19	Latvia	83.19
6	Germany	90.56	20	Malta	84.89
7	Greece	85.78	21	Netherlands	91.06
8	Denmark	92.31	22	Poland	84.32
9	Spain	88.71	23	Portugal	87.79
10	Estonia	87.26	24	Romania	78.35
11	Finland	91.89	25	Slovak Republic	83.15
12	France	88.78	26	Slovenia	87.71
13	Croatia	81.92	27	Sweden	91.62
14	Hungary	81.02	28	Ukraine	73.38

Table 5. Human Development Index of the EU and Ukraine. *Source: the study based on HDI 2020*

No.	Economy	HDI	No.	Economy	HDI
1	Austria	0.922	15	Ireland	0.955
2	Belgium	0.931	16	Italy	0.892
3	Bulgaria	0.816	17	Lithuania	0.882
4	Cyprus	0.887	18	Luxembourg	0.916
5	Czech Republic	0.900	19	Latvia	0.866
6	Germany	0.947	20	Malta	0.895
7	Greece	0.888	21	Netherlands	0.944
8	Denmark	0.940	22	Poland	0.880
9	Spain	0.904	23	Portugal	0.864
10	Estonia	0.892	24	Romania	0.828
11	Finland	0.938	25	Slovak Republic	0.860
12	France	0.901	26	Slovenia	0.917
13	Croatia	0.851	27	Sweden	0.945
14	Hungary	0.854	28	Ukraine	0.779

The Quality of Life Index (QLI), which is calculated by the international organization "Economist Intelligence Unit".
The study uses 9 quality of life factors to determine a country's score: health - life expectancy (in years); family life - divorce rate (per 1000 people), the score is from 1 (few divorces) to 5 (many divorces); public life - variable takes on the value 1 if the country has a high level of church attendance or union membership; material well-being - GDP per capita, purchasing power parity; political stability and security - ratings of political stability and security; climate and geography - latitude, to distinguish between cold and hot climates; job security - unemployment rate (in%); political freedom - average index of political and civil freedom (scale from 1 (completely free) to 7 (not free); gender equality - measured by dividing the average salary of men by the salary of women.
The EU countries and Ukraine distribution according to the Quality of Life Index [29] is given in Table 6.

As can be seen from the table, Austria, Finland, the Netherlands, Luxembourg have the highest level of quality and safety of life; the lowest have Ukraine, Romania, Bulgaria, Greece.

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Table 6. Quality of Life Index of the EU countries and Ukraine. *Source: the study based on QLI 2021*

No.	Economy	QLI	No.	Economy	QLI
1	Austria	182.37	15	Ireland	150.89
2	Belgium	150.89	16	Italy	138.63
3	Bulgaria	126.34	17	Lithuania	160.02
4	Cyprus	144.06	18	Luxembourg	183.31
5	Czech Republic	156.33	19	Latvia	147.59
6	Germany	176.76	20	Malta	144.06
7	Greece	129.86	21	Netherlands	183.31
8	Denmark	190.01	22	Poland	132.65
9	Spain	164.48	23	Portugal	161.91
10	Estonia	173.56	24	Romania	131.71
11	Finland	182.79	25	Slovak Republic	149.68
12	France	150.73	26	Slovenia	168.20
13	Croatia	156.10	27	Sweden	171.40
14	Hungary	134.01	28	Ukraine	107.35

3. The ecological measuring of sustainable development can be viewed using the Environmental Performance Index (EPI).
   The EPI index consists of 16 indicators that show the achievements of a country on its path to sustainable environmental development. These indicators include: the level of infant mortality (deaths per 1000 children 1-14 years old), chemical pollution and dustiness (μg/m^3) of the atmosphere, the provision of drinking water and its sufficient purification (%), the state of ozone, the content of nitrates in drinking water (mg / l), water consumption, share of natural and protected areas, degree of deforestation (%), level of agriculture support, depletion of fish stocks, share of alternative energy sources, energy efficiency and CO_2 emissions. All these evaluation criteria are presented in Table 7.

Table 7. Components of the Environmental Performance Index (EPI). *Source: the study based on EPI*

Group	Environmental Health		
Political categories	*Effects on human health*	*Air pollution affecting health*	*Water and sanitation*
Indicators	1. Infant mortality	2. The average number of particulate matter (PM 2.5)	5. Access to sanitation
		3. The percentage of the population exposed to elevated PM 2.5	6. Access to drinking water
		4. Indoor air pollution	
Group	Ecosystem vitality		
Political categories	*Climate change and energy*	*Water resources (effect on the ecosystem)*	*Biodiversity*
Indicators	7. The trend of carbon intensity	10. Wastewater treatment	11. Environmental protection
	8. Changing the trend of carbon intensity		12. Protection of the national biome
	9. The trend of the ratio of carbon dioxide emissions to kWh		13. Protection of the international biome
			14. Marine protected areas
Political categories	*Agriculture*	*Forest*	*Fishing*
Indicators	15. Agricultural subsidies	17. Changing of the forests area	18. Fishing on the coastal shelf
	16. Legislation governing the use of pesticides		19. Exploitation of fish resources

Country receives points for each indicator. The number of points depends on the position of the state within the range, the worst for this indicator (relative zero on a 100-point scale) and the desired goal (equivalent to one hundred points).

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All components are combined and calculated into a general index for each country, Table 8 [30].

Table 8. Environmental Performance Index of the EU countries and Ukraine. Source: the study based on EPI 2020

No.	Economy	EPI	No.	Economy	EPI
1	Austria	79.6	15	Ireland	72.8
2	Belgium	73.3	16	Italy	71.0
3	Bulgaria	57.0	17	Lithuania	62.9
4	Cyprus	64.8	18	Luxembourg	82.3
5	Czech Republic	71.0	19	Latvia	61.6
6	Germany	77.2	20	Malta	70.7
7	Greece	69.1	21	Netherlands	75.3
8	Denmark	82.5	22	Poland	60.9
9	Spain	74.3	23	Portugal	67.0
10	Estonia	65.3	24	Romania	64.7
11	Finland	78.9	25	Slovak Republic	68.3
12	France	80.0	26	Slovenia	72.0
13	Croatia	63.1	27	Sweden	78.7
14	Hungary	63.7	28	Ukraine	49.5

As Table 8 shows, Luxembourg, Denmark, France pursues the most effective environmental policy according to the study; the worst – Bulgaria and Ukraine.
Economic component of sustainable development is the resulting score of a country according to The Global Competitiveness Index, Global Innovation Index and Index of Economic Freedom, Table 9 and Fig. 1. This is the third stage of the calculation algorithm. Previously, the average values of the indicator for each of the ratings were found and the score of each country in the rating was standardised by dividing the rating score by the average value.

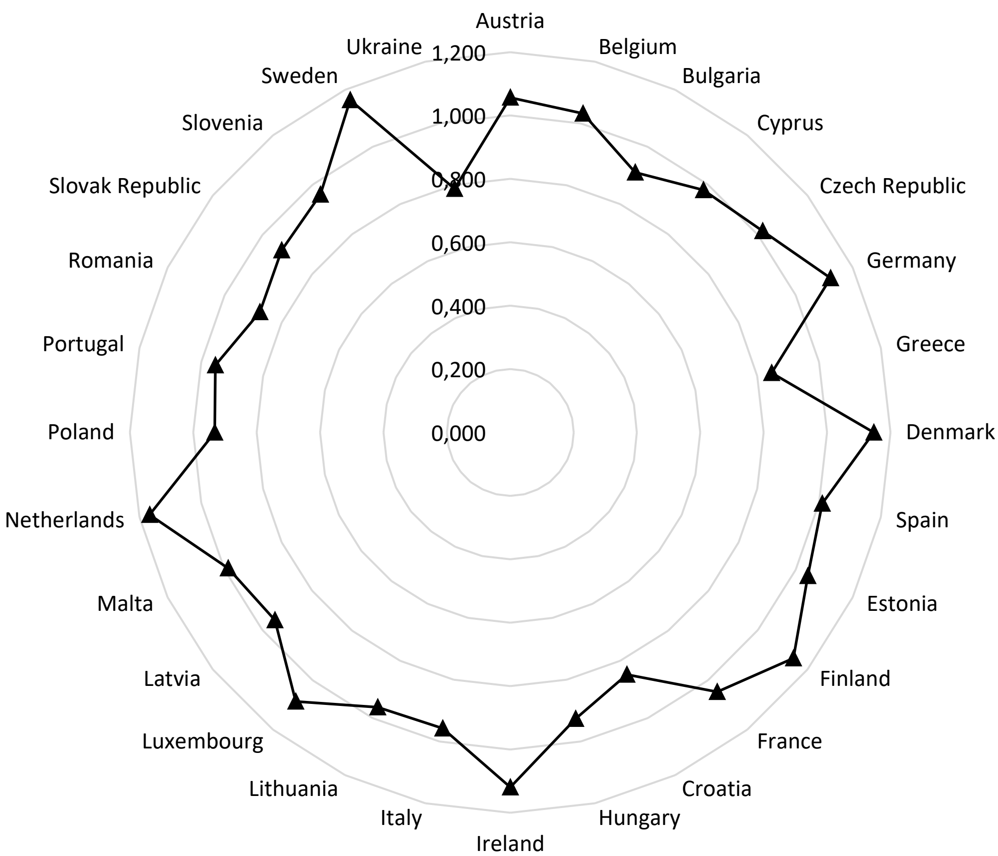

Fig.1. Economic component of sustainable development of the EU countries and Ukraine. *Source: own calculations based on GCI WEF 2019; GII 2019; IEF 2021*

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Table 9. Economic component of sustainable development of the EU countries and Ukraine.
Source: own calculations based on GCI WEF 2019; GII 2019; IEF 2021

Country	GCI	GII	IEF	Economic component of sustainable development
Austria	1.071575	1.055689	1.042838	1.057
Belgium	1.068372	1.039938	0.989215	1.032
Bulgaria	0.907723	0.83622	0.993448	0.910
Cyprus	0.928571	1.001806	1.00756	0.979
Czech Republic	0.991058	1.024395	1.041427	1.019
Germany	1.144134	1.205939	1.023082	1.122
Greece	0.875352	0.80617	0.859389	0.846
Denmark	1.135439	1.21112	1.097873	1.147
Spain	1.052976	0.991651	0.986393	1.010
Estonia	0.991818	1.035586	1.103518	1.043
Finland	1.122441	1.239927	1.073884	1.143
France	1.102307	1.124286	0.927124	1.047
Croatia	0.866364	0.783788	0.89749	0.848
Hungary	0.910242	0.922432	0.948292	0.927
Ireland	1.050693	1.162625	1.148675	1.120
Italy	1.000506	0.959529	0.915835	0.958
Lithuania	0.956073	0.859224	1.085173	0.962
Luxembourg	1.077436	1.108121	1.072473	1.086
Latvia	0.936893	0.895905	1.02026	0.950
Malta	0.958793	1.015691	0.990626	0.988
Netherlands	1.152466	1.273292	1.083762	1.167
Poland	0.96365	0.856115	0.98357	0.933
Portugal	0.985389	0.925334	0.952525	0.954
Romania	0.900178	0.76182	0.980748	0.876
Slovak Republic	0.933982	0.871451	0.963814	0.922
Slovenia	0.981938	0.937768	0.963814	0.961
Sweden	1.13645	1.319093	1.054128	1.165
Ukraine	0.797182	0.775084	0.793065	0.788

As it can be seen from Table 9 and Fig. 1, Germany, Denmark, Finland, Ireland, Luxembourg, Netherlands, Sweden have the highest economic development among the EU countries. The countries that have certain economic difficulties are: Bulgaria, Greece, Croatia and Ukraine.

Social component of sustainable development is the resulting country score of The Social Progress Index (SPI), Human Development Index (HDI) and Quality of Life Index (QLI), Table 10 and Fig. 2. This is the fourth stage of the calculation algorithm. Previously, the average values of the indicator for each of the ratings were found and the score of each country in the rating was standardised by dividing the rating score by the average value.

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Table 10. Social component of sustainable development of EU countries and Ukraine.
Source: own calculations based on SPI 2020; HDI 2020; QLI 2021

Country	SPI	HDI	QLI	Social component of sustainable development
Austria	1.036788	1.032888	1.174146	1.079
Belgium	1.036325	1.04297	0.971469	1.016
Bulgaria	0.925116	0.914139	0.81341	0.883
Cyprus	1.003657	0.993678	0.927496	0.974
Czech Republic	1.004237	1.008242	1.006493	1.006
Germany	1.049067	1.060895	1.138027	1.082
Greece	0.993695	0.994799	0.836073	0.938
Denmark	1.06934	1.053053	1.223334	1.113
Spain	1.027637	1.012723	1.058965	1.033
Estonia	1.01084	0.99928	1.117425	1.041
Finland	1.064474	1.050812	1.17685	1.096
France	1.028448	1.009362	0.970439	1.002
Croatia	0.94898	0.953349	1.005013	0.969
Hungary	0.938554	0.95671	0.862791	0.918
Ireland	1.046635	1.069857	0.971469	1.028
Italy	1.011998	0.99928	0.892536	0.966
Lithuania	0.972727	0.988077	1.030251	0.997
Luxembourg	1.037483	1.026166	1.180198	1.079
Latvia	0.963692	0.970153	0.950223	0.961
Malta	0.983385	1.002641	0.927496	0.971
Netherlands	1.05486	1.057534	1.180198	1.096
Poland	0.976782	0.985837	0.854035	0.937
Portugal	1.016979	0.967912	1.042419	1.009
Romania	0.907624	0.927583	0.847983	0.894
Slovak Republic	0.963228	0.963431	0.963679	0.963
Slovenia	1.016052	1.027287	1.082916	1.042
Sweden	1.061347	1.058654	1.103518	1.074
Ukraine	0.85005	0.872689	0.691147	0.800

Table 10 and Fig.2 show, that Austria, Germany, Denmark, Finland, Luxembourg, Netherlands, Portugal, Sweden have the highest social development among the EU countries. These countries have shown a high level of social responsibility. Among the countries that have certain social problems can be distinguished: Bulgaria, Greece, Hungary, Romania, as well as Ukraine. In general, it should be noted that the social inequality of the studied countries is not significant.

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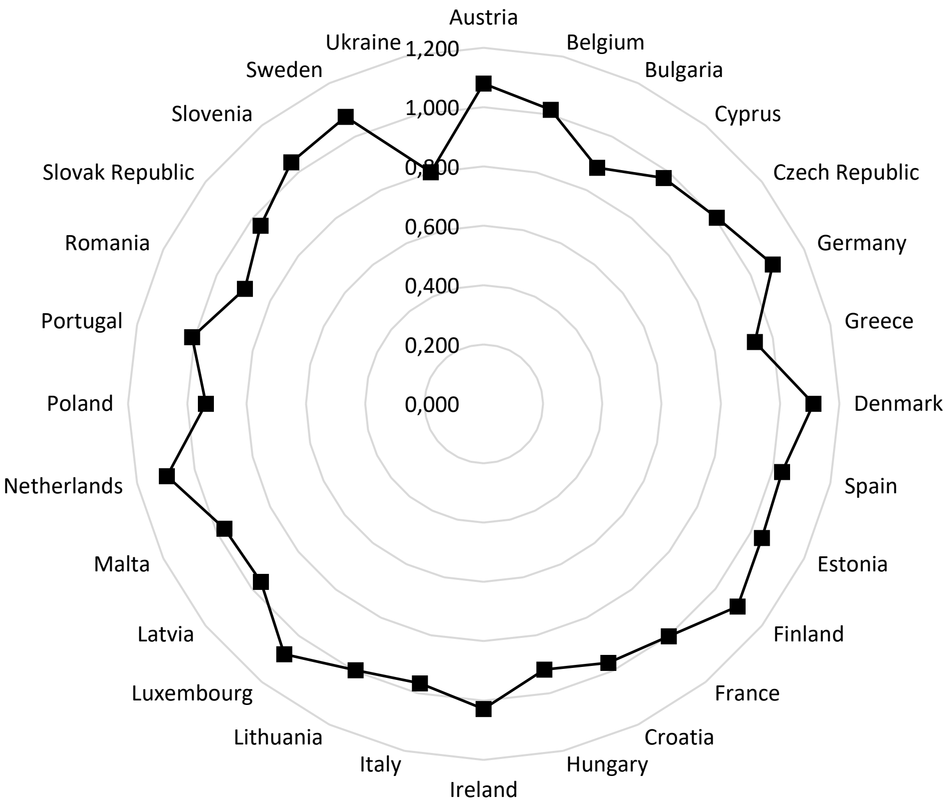

Fig. 2. Social component of sustainable development of EU countries and Ukraine
Source: own calculations based on SPI 2020; HDI 2020; QLI 2021

The environmental component of sustainable development is the result of the country's environmental performance score, Table 11 and Fig. 3. This is the fifth stage of the calculation algorithm. Previously, the average value of the indicator was found and the score of each country in the ranking was standardized by dividing the rating score by the average value.

Table 11. Environmental component of sustainable development of EU countries and Ukraine.
Source: own calculations based on EPI 2020

No.	Economy	Environmental component of sustainable development	No.	Economy	Environmental component of sustainable development
1	Austria	1.138595	15	Ireland	1.041328
2	Belgium	1.04848	16	Italy	1.015581
3	Bulgaria	0.815326	17	Lithuania	0.899719
4	Cyprus	0.926897	18	Luxembourg	1.177216
5	Czech Republic	1.015581	19	Latvia	0.881124
6	Germany	1.104266	20	Malta	1.01129
7	Greece	0.988404	21	Netherlands	1.077088
8	Denmark	1.180077	22	Poland	0.871111
9	Spain	1.062784	23	Portugal	0.958365
10	Estonia	0.934049	24	Romania	0.925466
11	Finland	1.128582	25	Slovak Republic	0.97696
12	France	1.144317	26	Slovenia	1.029885
13	Croatia	0.90258	27	Sweden	1.125722
14	Hungary	0.911162	28	Ukraine	0.708046

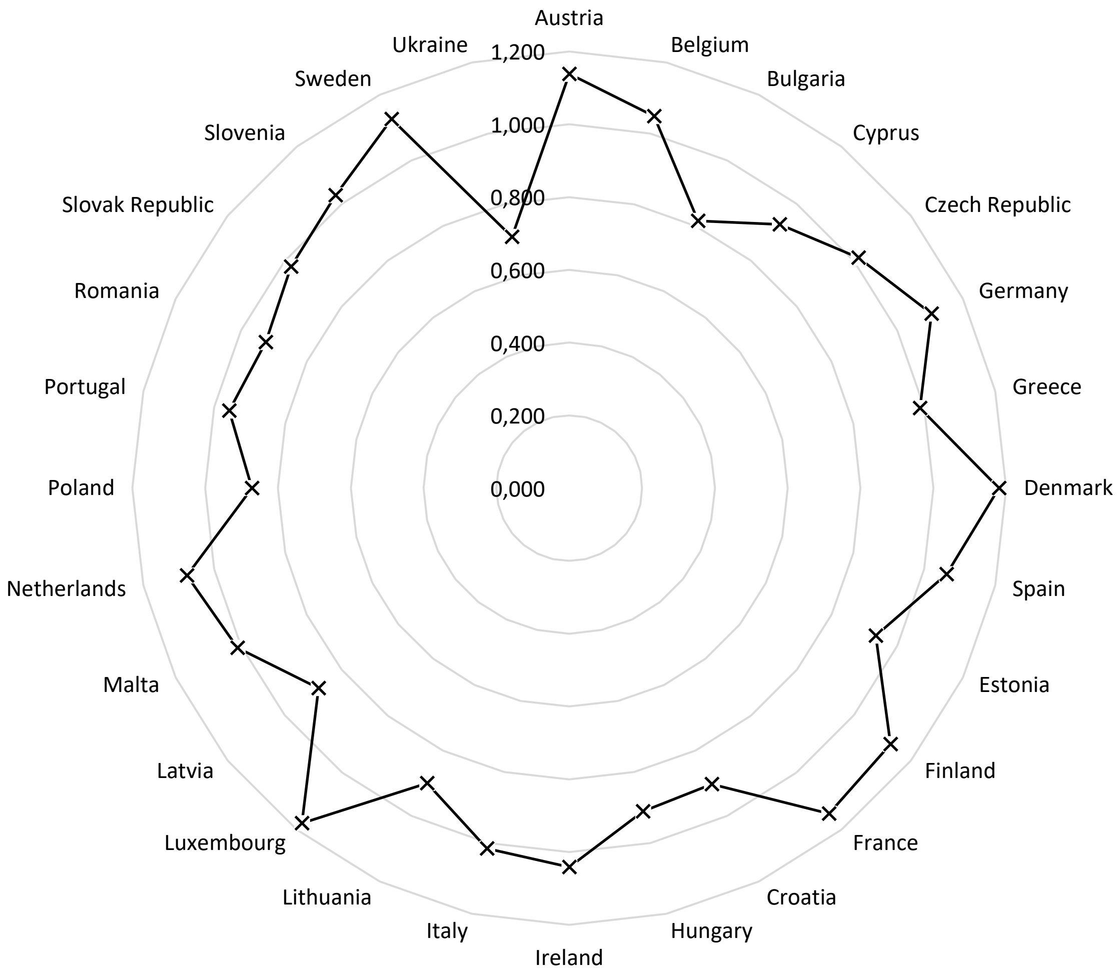

Fig. 3. Environmental component of sustainable development of EU countries and Ukraine
Source: own calculations based on SPI 2020; HDI 2020; QLI 2021

As can be seen from Table 11 and Fig. 3, Austria, Belgium, Germany, Denmark, Finland, France, Luxembourg, Netherlands, Sweden have the highest environmental sustainability. Among the countries that have a certain ecological instability we can note Bulgaria, Estonia, Greece, Croatia, Hungary, Lithuania, Latvia, Poland, and Ukraine.
Sustainable Development Index is calculated according to the methodology mentioned above, Table 12, Fig. 4 and 5. This is the sixth stage of calculating the index of sustainable development of the world using the index method and methodology for calculating the integrated index of human development, adapted to the indicators of sustainable development.

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Table 12. Components of the Sustainable Development Index of the EU countries and Ukraine.
Source: Author's

Country	Economic component	Social component	Environmental component	Sustainable Development Index
Austria	1.056635	1.079332	1.138595	1.090979
Belgium	1.031985	1.016402	1.04848	1.032206
Bulgaria	0.910206	0.882753	0.815326	0.868501
Cyprus	0.97864	0.974349	0.926897	0.959672
Czech Republic	1.018744	1.006323	1.015581	1.013536
Germany	1.121771	1.081956	1.104266	1.102544
Greece	0.846447	0.938449	0.988404	0.922532
Denmark	1.147187	1.11268	1.180077	1.146318
Spain	1.009894	1.032929	1.062784	1.034976
Estonia	1.042636	1.041188	0.934049	1.00464
Finland	1.143332	1.095958	1.128582	1.122449
France	1.047384	1.002457	1.144317	1.063096
Croatia	0.847831	0.968784	0.90258	0.905053
Hungary	0.926853	0.918435	0.911162	0.918794
Ireland	1.119535	1.02845	1.041328	1.062355
Italy	0.957999	0.966416	1.015581	0.979673
Lithuania	0.962422	0.996724	0.899719	0.9521
Luxembourg	1.085896	1.079074	1.177216	1.113179
Latvia	0.94963	0.96132	0.881124	0.930007
Malta	0.988095	0.970645	1.01129	0.98987
Netherlands	1.167249	1.09601	1.077088	1.112781
Poland	0.932722	0.936899	0.871111	0.913074
Portugal	0.954101	1.008626	0.958365	0.973386
Romania	0.876152	0.893749	0.925466	0.898225
Slovak Republic	0.92227	0.963446	0.97696	0.95394
Slovenia	0.961002	1.041679	1.029885	1.010219
Sweden	1.164769	1.074312	1.125722	1.120986
Ukraine	0.788385	0.800372	0.708046	0.764476

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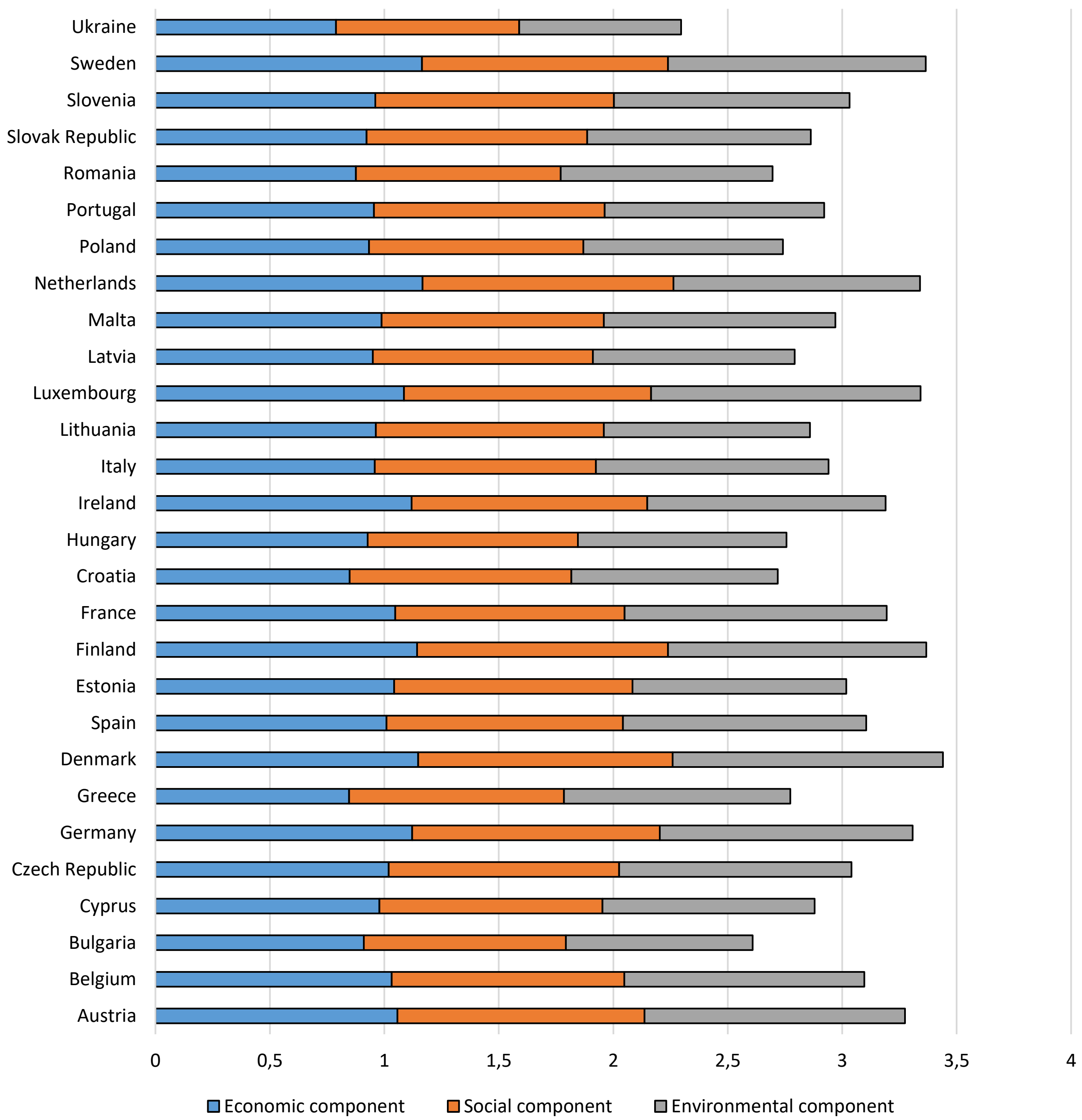

Fig. 4. Components of the Sustainable Development Index of the EU countries and Ukraine on the basis of equation (3). *Source: Author's*

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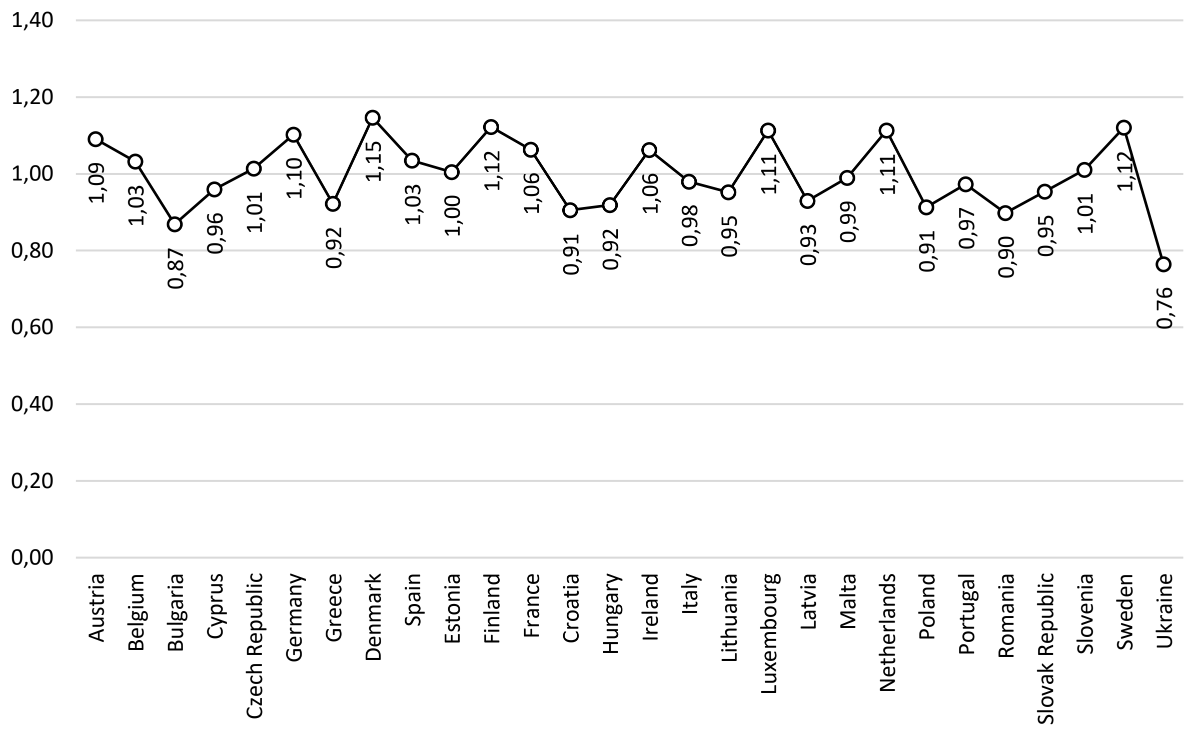

Fig. 5. Sustainable Development Index of the EU countries and Ukraine on the basis of equation (3)
Source: Author's

The average level of sustainable development in the EU countries is 0.998556 points. Therefore, Estonia, Slovenia, Czech Republic, Belgium, Spain, Ireland, France, Austria, Germany, Netherlands, Luxembourg, Sweden, Finland, Denmark have a high level of sustainable development. Greece, Latvia, Lithuania, Slovak Republic, Cyprus, Portugal, Italy, Malta have an average level of sustainable development. Hungary, Poland, Croatia, Romania, Bulgaria and Ukraine have an insufficient level of sustainable development.
To confirm the objectivity of the proposed calculation, a comparison was made between the data obtained by the authors and the data for the studied countries in the Sustainable Development Report (2021). The correlation coefficient, Sustainable Development Index, calculated by the authors, and the index, which consists of 17 groups of indicators and contains more than 100 criteria, is 0.66. This indicates a moderately high level of correlation, so it can be argued that the calculation proposed by the authors can be used in various studies of sustainable development.

Conclusions

1. The author's vision of the sustainable development index – multidimensional Sustainable Development Index is proposed and tested on the example of the EU countries and Ukraine, using the index method and the methodology for calculating the integral human development index, adapted to the indicators of sustainable development.
2. It has been substantiated the use of international ratings of Global Competitiveness Index, Global Innovation Index and Index of Economic Freedom as an economic component of the Sustainable Development Index. They allow assessing the state of the economy in terms of the level of innovation, international trade, institutional prerequisites, business environment, education system, etc.
3. Basing on the results of the calculation of the economic component, it was determined that Germany, Denmark, Finland, Ireland, Luxembourg, the Netherlands and Sweden have the highest economic development among the EU countries. The countries that have certain economic difficulties are: Bulgaria, Greece, Croatia and Ukraine.
4. In order to analyse the social component of the Sustainable Development Index, the use of the international ratings of Social Progress Index, Human Development Index and Quality of Life Index was determined. They allow assessing the social development of the country in terms of basic needs, basics of well-being, development opportunities, average life expectancy, educational level, etc.
5. Basing on the results of the calculations, it was determined that the highest social development among the EU countries have Austria, Germany, Denmark, Finland, Luxembourg, the Netherlands, Portugal, Sweden. These countries have shown a high level of social responsibility. Among the countries that have certain social problems can be distinguished: Bulgaria, Greece, Hungary, Romania, Ukraine.

6. It is proposed to consider the environmental measuring of sustainable development using the Environmental Performance Index. It records the country's achievements on its way to sustainable environmental development through the level of infant mortality, chemical pollution and dustiness of the atmosphere, the provision of drinking water and its sufficient purification, the state of ozone, the content of nitrates in water consumption, water consumption, share of natural and protected areas, level of deforestation, agriculture support level, depletion of fish stocks, share of alternative energy fill sources, energy efficiency and CO_2 emissions.
7. It is emphasised that Austria, Belgium, Germany, Denmark, Finland, France, Luxembourg, the Netherlands, Sweden have the highest environmental sustainability. Among the countries that have a certain ecological instability we can note Bulgaria, Estonia, Greece, Croatia, Hungary, Lithuania, Latvia, Poland, Ukraine.
8. Based on the results of the Sustainable Development Index calculation, it was concluded that Estonia, Slovenia, Czech Republic, Belgium, Spain, Ireland, France, Austria, Germany, Netherlands, Luxembourg, Sweden, Finland, Denmark have a high level of sustainable development; Greece, Latvia, Lithuania, Slovak Republic, Cyprus, Portugal, Italy, Malta have an average level of sustainable development; Hungary, Poland, Croatia, Romania, Bulgaria and Ukraine have an insufficient level of sustainable development.

Impact

To ensure sustainable development, the following initial conditions can be identified: economic development, which is supported on the basis of a modified market system; natural and ecological sustainability; close international cooperation to achieve the goals of sustainable development; sustainable social development based on the principle of justice (table 13).

Table 13. SWOT-analysis of the proposed calculation of the Sustainable Development Index.
Source: Author's

Strengths	Weaknesses
• simplicity and clarity of the proposed index • basing the calculation methodology for the well-known and proven global assessment methods • the possibility of comparison of rankings, developed on the basis of the author's methodology with the other, complementary rankings, prepared on the basis of traditional methodology; • the opportunity of assessing not only the level of sustainable development of any country, but also its economic, social and environmental components separately; • comprehensiveness important for various groups: administrative and statistical services at the level of countries, regions and international organizations and the academic community of social sciences as well; • opportunities to easily replace any component (rating) with another, make a calculation for other countries or add more if the study requires.	• dependence on world rankings and their imperfect and incomplete evaluation methods • duplicating errors resulting from traditional world rankings of the SDI; • delay in presenting rankings, based on the new SDI.
Opportunities	**Threats**
• the requirement for multidimensional assessment by administrative and statistical services at the level of countries, regions, international organizations and the academic community of social sciences; • the need to use of the most simple and easy understandable indicators of the sustainable development, which take into account as many aspects of economic, social and environmental life as possible; • the necessity to boost sustainable development in countries and regions around the world; • the opportunity to identify leaders of the sustainable development with the use of an objective measurement/ evaluation tool.	• originality • unwillingness to replace the already known the Sustainable Development Index with a new, more comprehensive one; • the need to revalue the existing world rankings with the new SDI; • the originality of the new method, developed by the academic community, not in statistics services; • the challenge of the introducing the new method of calculating SDI into the practice of the sustainable development evaluators.

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Thus, the calculation of the Sustainable Development Index and its components proposed by the authors on the example of the EU and Ukraine is based on objective international rankings that have a transparent calculation methodology, constant updating and cover most countries. The proposed calculation option has a clear algorithm that can be easily adapted to other countries, or the expansion of components. These aspects make it possible to identify the countries with the best level of economic, social and environmental development; calculate the index of sustainable development of any country in the world.

Conflict of interest
There are no conflicts to declare.

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