engineering proceedings

Proceeding Paper

Enhancing the Energy Efficiency of a Black Liquor Evaporation Plant by Mechanical Vapor Recompression Integration †

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† Presented at the 2nd International Electronic Conference on Processes: Process Engineering—Current State and Future Trends, Online, 17-31 May 2023

Abstract: Black liquor thickening in integrated multi-effect evaporation plant consumes substantial amount of steam produced in pulp and paper mills and its efficient operation is, thus, crucial. Industrial applications of heat pumps in pulp and paper industry, especially in black liquor evaporation, show promising in terms to cut down energy consumption and in decarbonizing this industrial branch. Modelling of such plant includes momentum, heat and mass transfer issues, enriched with black liquor material specification. An existing black liquor evaporation plant which thickens inlet black liquor from 17 % to 75. % wt. dry solids with dry solids flow of 2500 tonnes per day is considered. It already includes MVR (mechanical vapor recompression) pre-evaporator as well as water condensate stripping columns. Mathematical model of this plant is created in Matlab environment and, after verification of obtained results, it serves for analyses of possible plant modifications. Among the modification options, installation of a second MVR is modeled and its impact on the whole plant is examined. As a result, differential (marginal) change in steam and electricity consumed in the plant is obtained. Model results indicate the possibility of a reduction of process steam consumption of around 10 tonnes per hour and an increase of electricity consumption of 600 kW. A favorable simple payback period of 2.5 years can be expected for the considered investment.

Keywords: evaporator; black liquor; mathematical modelling; heat pump

Citation: Variny, M. Enhancing the Energy Efficiency of a Black Liquor Evaporation Plant by Mechanical Vapor Recompression Integration. *Eng. Proc.* **2023**, *5*, x. https://doi.org/10.3390/xxxxx

Published: 30 May

1. Introduction

Human society is facing climate change and its consequences and suitable actions need to be undertaken quickly to prevent it from becoming disastrous. Industry belongs to sectors where, despite the progress already achieved, a large improvement can still be achieved by reducing the use of fossil fuels, by switching to renewable energies and by increasing its energy and material efficiency [1]. Among the most energy-intense industry sectors, chemicals and refining, iron and steel and pulp and paper [2] can be named as, taken together, they stand for the majority of industrial fuel and energy consumed as well as for greenhouse gases released to the atmosphere [3,4].

Most of today's paper is made by sulphite process. During paper production process, significant amounts of valuable side products are produced. Their reuse lowers costs for purchasing chemicals and energies. Main substance considered is black liquor (BL) – dark, liquid residual material from wood chips cooking containing inorganic cooking chemicals and dissolved organics [5]. Inorganic compounds (namely Na_2CO_3 and Na_2SO_4) present in black liquor can be recovered by suitable method yielding an aqueous solution mixture of sodium sulphite (Na_2S) and sodium hydroxide (NaOH) termed white liquor (WL). Organic compounds (lignin, polysaccharides, low molecular weight carboxylic acids, methanol ...) can be easily combusted and the released heat represents a major part of heat produced for a paper mill's needs [6]. Kraft recovery process incorporates these two approaches into one process unit. First step of the process is diluted BL thickening in a multiple-effect evaporator train. During the stepwise BL thickening, volatile organic compounds (methanol and non-condensable organic gases) are released from BL and are concentrated and separated as side streams of the evaporator [7].

Multiple-effect evaporator found its application in various industrial spheres, such as dairy, sugar production, paper mills, inorganic brines concentration or water desalination [8,9]. It is heat-powered separation equipment, cascading heat supplied in form of low- or middle-pressure steam down to lower pressures and to vacuum, ending with lowest pressure steam being condensed in a condenser and heat being rejected to the environment. As an alternative, electricity-powered evaporation can be considered, recompressing the evaporated water to serve as heating medium. Such arrangement is termed Mechanical Vapor Recompression (MVR); being a kind of heat pump it gradually becomes applied in distillation processes [10,11] and evaporators [12,13]. It can both facilitate evaporation operation costs decrease and unit capacity increase, both effects being desired in industrial conditions [14,15].

The presented study aims at analyzing the current performance of a highly integrated black liquor evaporator in a large-scale paper mill, already equipped with an MVR unit processing half of the black liquor delivered to the evaporator. Mathematical model is developed and verified, serving for future evaporator operation assessment with a second MVR unit installed. The resulting energy consumption change is assessed, and primary energy consumption change is calculated. Simple payback period of such investment is estimated and its dependence on energies price and other factors is estimated. Thereby a contribution to industrial energy efficiency in pulp and paper mills is targeted.

2. Materials and Methods

2.1. Case Study Characterization

The considered evaporator consists of seven pressure levels and evaporator effects plus a MVR pre – evaporator (mechanical vapor recompression system).

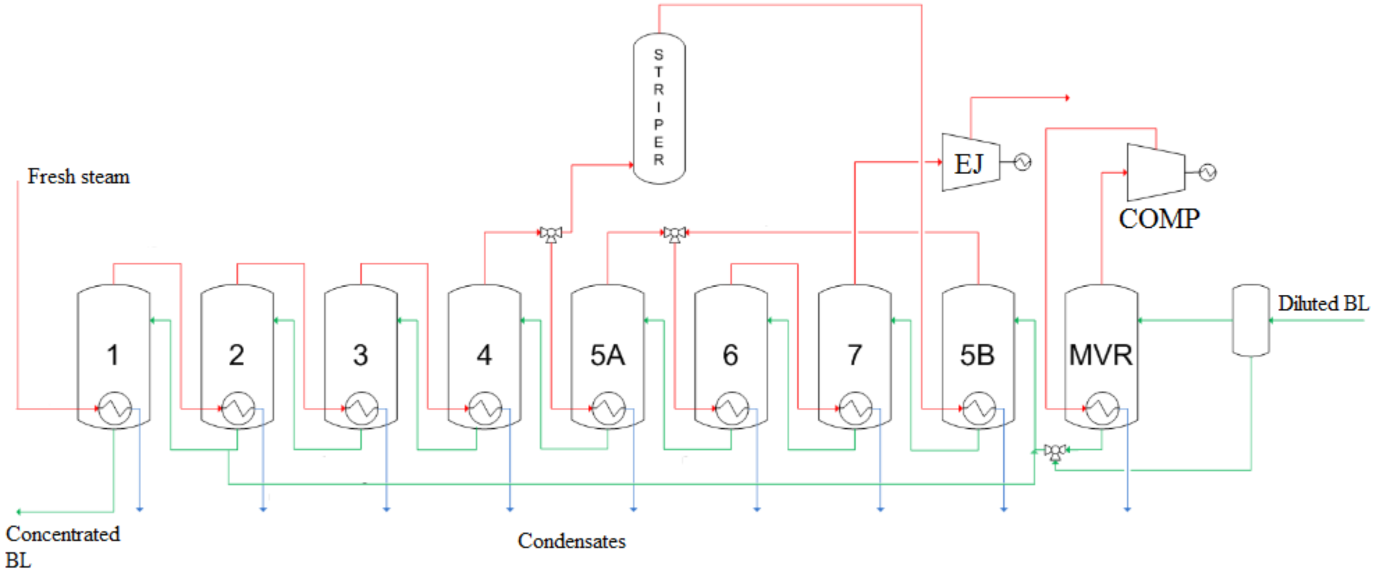

Figure 1. Schematic depiction of material streams considered in the evaporator train model, including black liquor streams (green), water steam streams (red) and steam condensates (blue). BL – black liquor, COMP – compressor, EJ – ejector, MVR – mechanical vapor recompression effect. Numbers 1 to 7 denote evaporator effects. Source: Own elaboration.

Evaporator processes 15 to 15.5 kt of diluted BL per day (2,500 t of dry solids per day) at full load. Diluted BL is split into two parts; half of it being fed to MVR effect, while the rest of it bypassing it. MVR system both secures additional pre – evaporation before entering the evaporation cascade and financial saving, based on lowering fresh steam amount consumed in evaporation plant. Diluted black liquor from cooking section of pulp mill contains circa 16 % dry solids (BLDS) by mass. Further processing of thickened black liquor in recovery boiler required the BLDS to be increased in the evaporator train to at least 70 % by mass. Schematic depiction of the evaporator is provided in Figure 1.

2.2. Model Description

Model input data consist of BLDS profile, inlet liquor flow, its temperature, corresponding dry solids amount and desired thickening level, driving forces in each effect, ratio of black liquor mass flow thickened in MVR to total black liquor mass flow and MVR conditions (effect temperature and compression adiabatic efficiency). Model outputs include temperature and pressure profile. Model is based on mass and energy balances of the evaporator train and includes exchanged heat calculation in each heat exchanger. The BL exhibits boiling point rise (BPR) compared to pure water, meaning its boiling temperature is higher than that of pure water at the same pressure. Clay's equation [16], equation (1) was adopted to calculate the BPRs in all effects.

$$\mathrm{BPR}\ (^\circ\mathrm{C}) = 7.4 \cdot 9.1 \cdot \mathrm{DS}/(8.1 - 7.1 \cdot \mathrm{DS}) \tag{1}$$

with DS denoting dry solids mass fraction. To reach desired output (= calculate temperature profile), following mathematical criterion, $f_{(i)}$, was used, equation (2)

$$f_{(i)} = \sum_{i} (\Delta Q_i)^2 = \min \tag{2}$$

with i denoting individual evaporator effects and ΔQi represents the difference between the calculated heat flux and the heat flux resulting from heat balance of the given evaporator effect. Once the temperature profile was estimated, pressure profile was calculated using steam tables [17] and considering the BPRs. Calculation evolution diagram is provided in Figure 2.

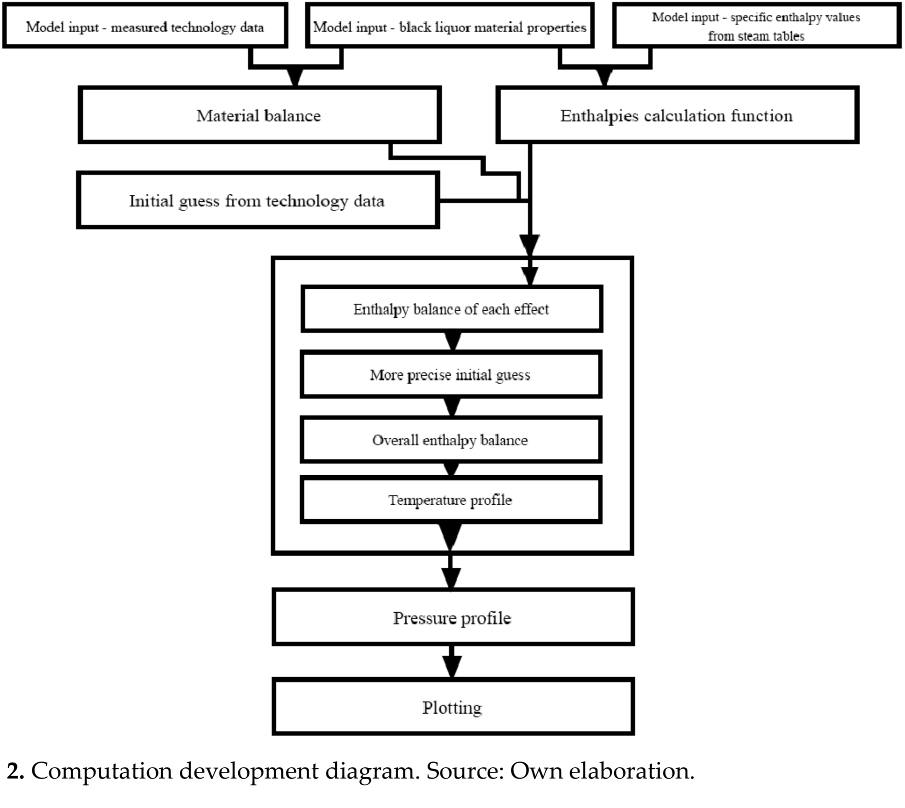

Figure 2. Computation development diagram. Source: Own elaboration.

Considering the results of mass and energy balance of the evaporator, its coefficient of performance (COP) can be defined, equation (3)

$$\text{COP} = (\text{Water evaporation rate excluding water evaporated in MVR})/(\text{Fresh steam consumption}) \tag{3}$$

Considering evaporator's operation in two states, A and B, differing in throughput, and, thus, in water evaporation rates and fresh steam consumption, the marginal COP, COP$_m$, can be defined, equation (4)

$$\text{COP}_m = (\text{Difference in water evaporation rates excluding water evaporated in MVR})/(\text{Difference in fresh steam consumption}) \tag{4}$$

Future operational state – C – is derived from A by adding an identical MVR to the existing one to be operated in parallel. This plant layout modification yields a decrease in fresh steam consumption and an increase in electricity consumption. The resulting change in energy efficiency of the evaporator can be assessed by evaluating the Differential Primary energy savings (DPES), equation (5)

$$\text{DPES} = (\text{Difference in fresh steam consumption}) \cdot \Delta_{cond}h/\eta_{ref,heat} + (\text{Difference in power consumption})/\ \eta_{ref,e} \tag{5}$$

where the difference of fresh steam consumption is expressed in t/day, $\Delta_{cond}h$ stands for latent heat of fresh steam condensation and amount to 2,080 MJ/t (0.578 MWh/t) [18] and the difference in power consumption amounts to 14.4 MWh/day (0.6 MW). $\eta_{ref,heat}$ stands for thermal efficiency of steam production from fuel and its value of 0.85 is assumed for steam boiler fired by black liquor. $\eta_{ref,e}$ denotes the thermal efficiency of a fossil fuel-based power plant deemed to provide extra power needed to drive the new MVR compressors with a value of 0.4. Negative DPES value indicates that primary energy (fossil fuel) is saved because of new MVR implementation.

2.2. Model Inputs

Model inputs for two current operational states, A and B, are summed up in Table 1.

Table 1. Characterization of model inputs for two operational states, A and B. BL – black liquor, BLDS – Black liquor dry solids content, MVR – mechanical vapor recompression unit.

Current operational state A (high evaporator throughput)								
Effect	**5B**	**7**	**6**	**5A**	**4**	**3**	**2**	**1**
Heat transfer driving force (°C)	4.4	4.2	5.1	5.8	2.0	3.8	5.5	2.9
BLDS (mass %)	19.7	22.9	23.1	25.9	30.7	36.4	44.7	73.1
MVR Inlet BLDS (mass %)	16.7	**Inlet BL mass flow (t/day)**			15,407	**Inlet BL temperature (°C)**		86
Current operational state A (low evaporator throughput)								
Heat transfer driving force (°C)	3.8	4.2	4.9	5.3	2.7	6.4	8.6	3.4
BLDS (mass %)	18.8	23.1	25.2	27.3	30.2	35.1	43.1	74.3
MVR Inlet BLDS (mass %)	15.8	**Inlet BL mass flow (t/day)**			13,835	**Inlet BL temperature (°C)**		82

Further model inputs included the following parameters, based on real evaporator operation: ratio of BL thickened in MVR of 0.5; temperature in MVR effect of 80 °C; condensing temperature of recompressed steam in MVR effect heater of 85 °C; isentropic steam compression efficiency of MVR compressor of 80 %. According to equipment documentation, the MVR compressor consumes 600 kW of electricity at full load operation.

Economic evaluation of second MVR unit incorporation in the existing evaporator, being operated in parallel with the first one, is based on following assumptions: fresh steam cost of 25 EUR/t, electricity cost of 150 EUR/MWh, 7000 hours of operation per year. Total MVR capital cost estimate for second MVR unit commissioning of 3.2 million EUR resulted from consultations with plant's managers, reviewing capital costs associated with the first MVR unit commissioned a few years ago.

3. Results

3.1. Temperature and Pressure Profiles

Comparison of obtained and measured temperature profiles along with calculated pressure profiles is provided in Figure 3.

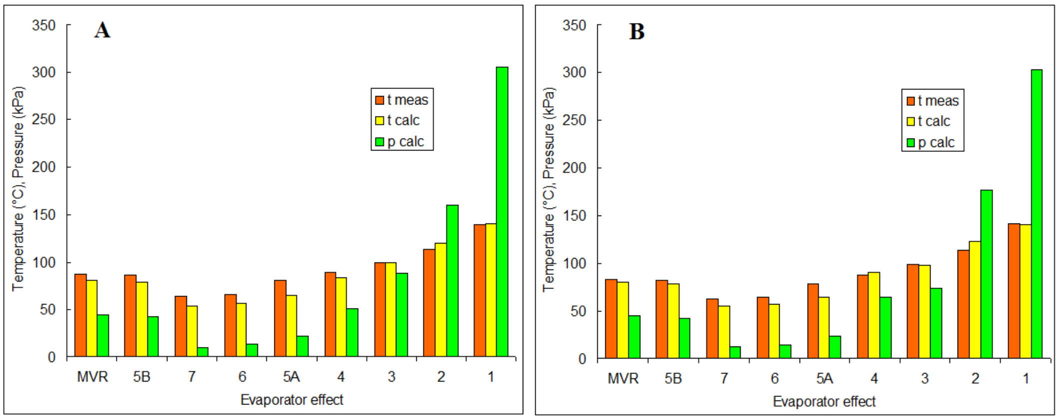

Figure 3. Temperature (t) and pressure (p) profiles for operational states A (left hand) and B (right hand). Calc – calculated, meas – measured. Source: Own elaboration.

Comparison of obtained and measured temperature profiles along with calculated pressure profiles is provided in Figure 3. Differences between calculated and measured values are acceptable, mostly below 10 °C and the temperature trends are similar. Considering the pressures, one sees that except effect 1 and 2, the evaporator operates in vacuum. Pressure measurement in vacuum evaporators with risk of foaming, solids crystallization and droplets entrainment in steam flows can be troublesome and decreased accuracy can be expected. No reliable measured data could be provided for this study by plant's operators, thus, pressure profile comparison is not possible.

3.2. Mass and Heat Balance

Obtained mass and heat balance results are summed up in Table 2. As can be seen, state B is characterized by around 10 % total water evaporation rate compared to state A. However, there is just a modest decrease in water evaporation in MVR unit. Measured and calculated steam consumptions agree very well in both states, proving the developed evaporator model as suitable for further calculations. In combination with previous results shown in Figure 3 it can be stated that model verification was successful. It is worth noting that the COP value lowers with decreasing throughput, reflecting the well-known fact that evaporators operate most efficiently at full throughput. Marginal COP value is significantly higher, exceeding 6, corroborating the previous finding. Thus, fresh steam saving due to second MVR implementation will be lower than expected if the simple COP values are considered.

State C is derived from state A in terms of BL throughput by modifying the equipment by a new MVR addition. The fraction of diluted BL delivered to evaporator, processed in MVRs rises, as a result, to 100 %. As a consequence, a larger fraction of water is evaporated in the MVRs, followed by lower fresh steam consumption compared to state

A by 263 t/day. Evaporator COP in this state is visibly lower than in state A, it is even lower that in state B.

Table 2. Summary of mass and heat balance of the evaporator in two current operational states, A and B and after second MVR effect implementation, state C. COP – Coefficient of performance.

Operational state	**A**	**B**	**C (2 MVRs)**
Water evaporated (t/day)			
Total	11,887	10,884	11,887
In MVR	2,346	2,208	4,314
In other effects together	9,541	8,677	7,573
Fresh steam consumed (t/day)			
Calculated	2,772	2,638	2,509
Measured	2,754	2,618	-
Evaporator COP[1] (t/t)	3.44	3.29	3.02
Marginal evaporator COP[1] (t/t)	6.45		-

[1] Water evaporated in MVR excluded.

DPES criterion, equation (5), evaluated from the difference in fresh steam and power consumption in states C and A yields a value of -142.8 MWh/day. Primary energy consumption in state A, obtained by equation (5) substituting the differences in energies consumption by their absolute values in state A, is 1,921 MWh/day. This indicates that new MVR implementation in the evaporator can lower its primary energy consumption by more than 7 %, making it more energy efficient and more environmentally friendly.

Comparison of states C and A allows for calculating the saving of operational expenses associated with second MVR unit operation: Decrease of steam consumption yields a 6,575 EUR/day saving, while the increase of power consumption amount to 2,160 EUR/day extra expenses. Thus, 4,415 EUR/day or 1.29 million EUR per year can be saved. The resulting simple payback period (PBP) is 2.5 years which highlights the feasibility of new MVR commissioning. However, PBP is very sensitive to steam price: a decrease by 50 % prolongs the PBP to almost 10 years. Electricity price increase by 50 % yields only a modest PBP increase to 3.3 years.

4. Discussion

The presented energy saving measure goes hand in hand with industry electrification that should result in greenhouse gases emission reduction, switching from fossil fuels to renewable energy sources (RES)-based electricity. In the particular case of pulp and paper industry, most of the consumed energy comes from black liquor combustion and the resulting heat and power cogeneration on steam turbines. Implementing electrification measures, such as MVR installation, reducing fresh steam consumption, might not lead to fuel saving in the end – the decisive fact is whether the paper mill's marginal steam source is fossil-based (natural gas) or RES-based (black liquor, bark, wood chips) [19]. Black liquor is not a tradable fuel; it must be combusted in the paper mill to ensure cooking chemical recovery. Thus, fresh steam consumption reduction in the paper mill can result either in excess steam venting, or to an increase of condensing electricity production provided a spare capacity is available in condensing part of steam turbines installed in the paper mill. Thus, actual and planned future steam balance should be carefully reviewed on-site to correctly assess the energy and economy impact of electrification measures in industry in general.

Fresh steam consumed in paper mill's evaporators has a pressure of 4 to 6 atmospheres while that of live steam produced in large paper mills can range between 4 and 10 MPa [9,20]. The pressure difference between produced steam and steam demand in the mill is utilized in steam turbines, cogenerating electricity. This makes the DPES estimation less straightforward and, eventually a more complex way of its calculation should be adopted that in this study. First, steam consumption reduction is associated with an in-house decrease of electricity production that might exceed 100 kWh/t, as shown in a similar study devoted to electricity-driven heat pump installation in a refinery [21]. Second, the resulting fuel consumption change would include more heat per ton of steam than just the evaporation heat, as a significant boiler feedwater subcooling and a significant steam superheat (both of the order of 0.1 MWh/t) should be considered. These two effects counteract each other in energy and economy impact estimation so that, under circumstances, the simplified approach adopted in this study can be adopted.

Black liquor processing capacity of the evaporator deserves attentions as well. Following the general trends of production capacities increase, including that of paper mills, evaporator can eventually become the bottleneck of production. For highly integrated multiple-effect evaporator, such as in this study, a further evaporation capacity extension via evaporator refurbishment might be very costly. An MVR-based pre-evaporator addition or its intensification can be a simpler and less costly option in such situation and might represent an additional incentive for plant managers to choose this option.

4. Conclusions

This study analyzes the energy and economy aspects of integrating an additional MVR to an existing highly integrated black liquor evaporator, already equipped with an MVR. The incentive for such study can be found in industry decarbonization efforts which can be partly achieved by electrification of energy-intensive industries. For this purpose, a model of the existing evaporator (15.5 kt/day diluted black liquor processing rate) is developed and verified using two sets (state A and B) of operational data. As states A and B differ in processes BL mass flow, their modeling and comparison provides an insight how the evaporator performs at lower evaporation rates. The obtained coefficient of performance values of 3.44 and 3.29, respectively, (excluding the MVR contribution) indicate worsened evaporator efficiency at lower throughputs.

The developed evaporator model is able to describe the temperature profile sufficiently, which, coupled with very good agreement between calculated and measured fresh steam consumption rates in states A and B, allows for claiming the model verified and ready to be used for future state modeling. State C is derived from state A by adding the second MVR unit, identical to the first one, while leaving the black liquor processing rate unchanged. As a result, evaporator's coefficient of performance in state C reaches just 3.09. Despite this, fresh steam consumption rate is decreased by over 260 t/day in exchange for power consumption increase by over 14 MWh/day. The resulting differential primary energy saving in state C, compared to A, yields an over 7 % decrease in primary energy use.

Economic parameters of second MVR unit installation are very sensitive to fresh steam price and less sensitive to electricity price. With basic set of prices (steam: 25 EUR/t, electricity: 150 EUR/MWh) an attractive simple payback period of 2.5 years with expected total investment of 3.2 mil. EUR is obtained. Attention should be paid to steam price variations; it can be derived from natural gas price fluctuations in last few years provided natural gas is marginal fuel for steam production in the paper mill. Marginal fuel may change along with the season of the year as a result of changing space heating requirements and heat losses to the surroundings; therefore, a more detailed assessment of any investment proposal impacting steam and electricity balance of any industrial enterprise is recommended as a future extension of this study.

Funding: This work was supported by the Slovak Research and Development Agency, Grant No. APVV-18-0134.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data obtained by calculations are included in this contribution.

Conflicts of Interest: The author declares no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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