Exergy Consumption of Cloud Computing: A Case Study

Slavisa Aleksic and Mehdi Safaei

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(Invited Paper)

***Abstract*—Although information and communication technology (ICT) has been playing an important role in the development of business and society for more than thirty years, its potential benefits and risks for the environment are still not sufficiently explored. This is mainly because of the complex interdependencies between ICT and different other areas of business and society that together build a very complex ecosystem.**

In this paper, we present a holistic approach that treats ICT as a part of the global ecosystem. This approach combines data-centric methods that are typically used to analyze communication networks with widely applicable thermodynamic tools. The proposed approach is well suited to investigate complex heterogeneous systems and assess their environmental sustainability. In particular, we briefly present and discuss the application of such an approach on an exemplary model of cloud computing use in Austria.

I. Introduction

Cloud computing has already become an integral part of corporate information technology and cloud-based services have penetrated many areas of the social and economic life. On the one hand, cloud computing promises an efficient usage of the computation and storage resources. Furthermore, cloud-services could be used in the future to optimize various processes and, consequently, to support new strategies and mechanisms for a sustainable exploitation of natural resources. On the other hand, the ever increasing number of cloud clients and intensive usage of cloud services leads to a continuous increase of ICT-related energy consumption. Additionally, the short lifetime of devices and services cause an increased usage of resources, production intensification, and more hazardous e-waste, which can harm the environment.

In this paper, we present a holistic approach for treating the environmental impacts of cloud computing that concentrates on the complete life cycle of ICT equipment and makes use of a widely applicable thermodynamic concept of exergy. This approach we refer to as *exergy-based life cycle assessment (E-LCA)*. The approach is applied to estimate environmental impacts of cloud computing. In particular, we show preliminary results of a case study that performs E-LCA on a cloud computing model for Austria. Although this approach can be used to investigate heterogeneous systems and to estimate the influence of both direct and indirect impacts of ICT on the environment, we concentrate here on direct impacts only, which means that we take into consideration only the impacts related to the life cycle of ICT hardware and not those that result from the change in production, transport, and consumption processes due to the applications of ICT.

The paper is organized as follows. The next section shows the basics of the E-LCA approach. The cloud model for Austria is presented in Section III. In Section IV, we show and discuss preliminary results. Finally, Section V summarizes and concludes the paper.

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II. Exergy-based Lifecycle Analysis

A very useful quantity that stems from the second law of thermodynamics is *exergy*. It can be used to clearly indicate the inefficiencies of a process by locating the degradation of energy. In its essence, exergy is the energy that is available to be used, *i.e.*, the portion of energy that can be converted into useful work. In contrast to energy, it is never conserved for real processes because of irreversibility. Any exergy loss indicates possible process improvements. The exergy of a macroscopic system is given by:

$$Ex = U + P_r V - T_r S - \sum_i \mu_{r,i} n_i \tag{1}$$

where extensive system parameters are internal energy (U), volume (V) and the number of moles of different chemical components, i (n_i), while intensive parameters of the reference environment are pressure (P_r), temperature (T_r) and the chemical potential of component i ($\mu_{r,i}$). The relation of exergy loss to entropy production is given by:

$$Ex_{loss} = Ex_{in} - Ex_{out} = T_r \Delta S \tag{2}$$

where ΔS is the entropy (irreversibility) generated in a process or a system. In other words, for processes that do not accumulate exergy, the difference between the total exergy flows into and out of the system is the exergy loss due to internal irreversibilities, which is proportional to entropy creation. The overall exergy loss of a system is the sum of exergy losses in all system components, *i.e.*, $Ex_{loss,total} = \sum Ex_{loss,component}$.

Exergy analysis has been performed in industrial ecology to indicate the potentials for improving the use of resources and minimizing environmental impact. The higher the exergy efficiency is, *i.e.*, the lower exergy losses, the better the sustainability of the considered system or approach.

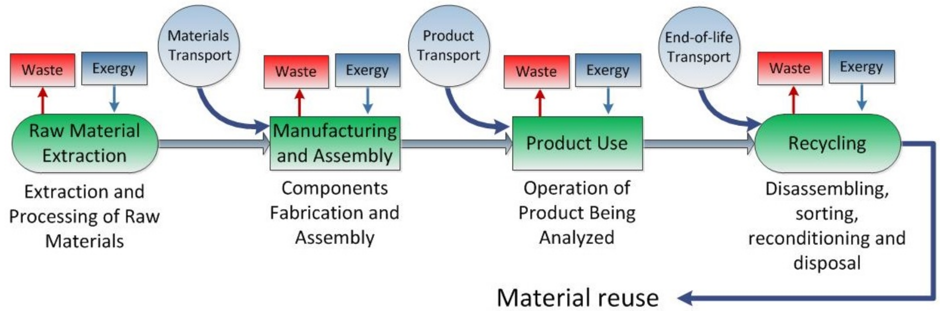

Fig. 1: *Lifetime exergy consumption flow*

Life cycle assessment (LCA) is a technique to evaluate environmental impacts of a product or a process over its entire life cycle (i.e., raw material extraction, manufacture, transportation, operational, maintenance, and recycling phases). LCA analysis provides a system perspective across the whole life time to define the system boundaries and aid decision making for system optimization and product selection.

An approach that combines the exergy concept with the LCA analysis we refer here to as the exergy-based LCA (E-LCA). Fig. 1 visualizes the approach of E-LCA across the whole product's or system's lifetime. Since the E-LCA approach considers all exergy inputs during the whole life cycle and we assume here that there is no accumulation of exergy, the overall exergy losses accumulated during the product's or system's lifetime equals the total exergy consumption. Thus, the overall lifetime exergy consumption is an effective measure of product's or system's environmental sustainability.

Since exergy-based analysis is a universally applicable method to assess process efficiency, it is well suited to investigate the sustainability of heterogeneous systems [1-3]. Since recently, E-LCA has also been used to assess the sustainability of ICT infrastructure and applications [4-7].

III. Model Description

In this section, we present the considered model, which we used to estimate the lifecycle exergy consumption related to the introduction and use of cloud computing in Austria within the time period from 2012 to 2020. The model used in this case study comprises several submodels such as those for core networks, access networks, data centers as well as different scales of enterprise computing infrastructures for small, medium and large scale enterprises including IT equipment, network infrastructure and end-user devices (see Fig. 2).

A. Network Model

The network core model includes core switches and routers having capacity of about 1 Tb/s, which are placed across Austria and connected through fiber cables. As regards the operational phase of access networks, we used a model that has been developed and used to estimate the energy consumption of an Austria-wide network [8]. To provide mobile access to cloud users, we modeled a UMTS radio access network comprising base transceiver stations (Node B) and radio network controllers (RNC) as well as serving GPRS support nodes (SGSN) and gateway GPRS support nodes (GGSN). We assumed that the wireless backhaul is realized mostly using microwave links (95%), but also copper cables (4%) and optical fibers (1%) are considered for the backhaul. The network model considers various data on technology penetration, market shares and population densities as well as typical core and access network architectures. The statistical data for Austria are obtained from several sources such as the Statistics Austria, the Austrian Regularity Authority for Broadcasting and Telecommunications (RTR), Austrian network operators and the Forum Mobilkommunikation (FMK). The main assumptions made for E-LCA of RAN are listed in Table I. For a more complete description of the access network model, the reader is refereed to [5,6,8].

B. Electricity Generation

While estimating the total exergy consumption of the operational (use) phase, we assumed three different electricity production sources as typically used in Austria [9]. The considered sources include hydroelectric power plants, fossil-fuel power plants and renewable (i.e., photovoltaic and wind turbine) power plants. In particular, hydropower plants play a substantial role in the Austrian energy sector. As reported in [9], around 58% (41 GWh) of the total electricity produced in Austria was originating from hydroelectric power stations in 2010. Hence, we assume that 58% of the total electrical energy consumed by the ICT equipment is generated by hydroelectric power plants, 35% by fossil-fuel power plants and 7% by renewable energy sources. Additionally, we considered the specific exergy losses for different electricity generation methods, both the waste of exergy due to the transmission losses and internal exergy destruction due to irreversibilities of the energy conversion. The considered energy efficiencies of hydroelectric power plants, fossil-fuel power plants, wind turbine systems and solar photovoltaic systems are 90%, 36%, 88.5% and 25%, respectively [3,6,8].

C. Model of Data Centers

For the cloud model for Austria, we assume that there are 10 medium-scale data centers, of which 4 are located in Vienna [10], and one large cloud data center. We considered a typical realization of data centers using the three-tier architecture. Based on the forecasts in [11-13] we defined scenarios for the development of cloud computing in Austria from 2012

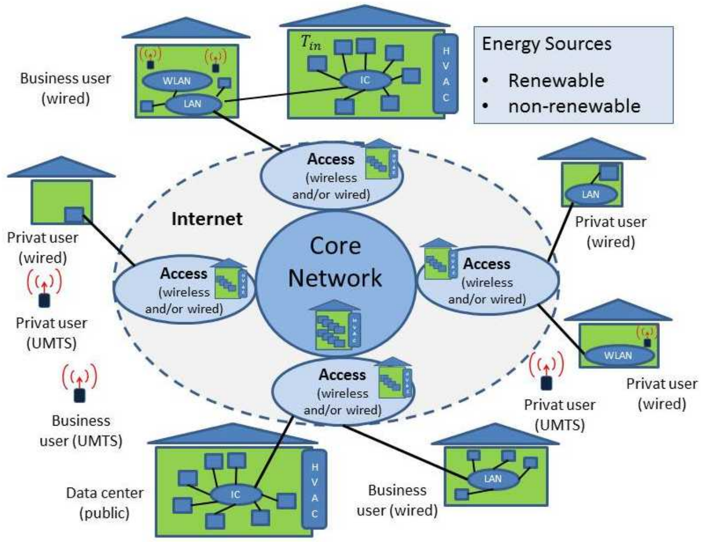

Fig. 2: *Schematic representation of the model used for the exergy-based life cycle assessment of cloud computing*

TABLE I: *Main assumptions for the exergy-based lifecycle analysis (E-LCA) of a radio access network.*

E-LCA Phases	The Case with 40% Material Reutilization
Raw Material Extraction	Spatial context: southeast Asia/China Material supply: within the radius of 1,000 km 40% of material flows from the recycling phase
Material Transportation	Spatial context: within the radius of 5,000 km Mode of transportation: rail/truck
Manufacturing and Assembly	Spatial context: southeast Asia/China
Product Transportation	From southeast Asia/China to Austria Mode of transportation: rail/truck/ship
Operation (Network Design Parameters)	Lifespan: 9 years Area coverage: 95% Backhaul: 95% radio link, 4% fiber, 1% copper Cell diameter: 300 m–500 m Cell type: macro No. of sectors: − 1 sector: 2% − 3 sectors: 97% − 4 sectors: 1% No. of network operators: 3 No. of sites (estimated/actual): 2,385/2,571
End-of-Life Transportation	From northeast Austria to southeast Asia/China Mode of transportation:rail/truck/ship
Recycling	Based on the mass of equipment Approximately 520 kJ/kg exergy consumption [4]

until 2020 that include the predicted trends in network traffic, number of users and usage intensity.

In general, the exergy consumed over the entire lifetime of the system (i.e., the *total cumulative exergy*) can be divided into two components. The first component is related to the so called *embodied exergy*, which is the exergy used for material extraction, transportation, manufacturing and recycling. The second component is composed of the electricity consumption of both IT equipment (including the internal network) and cooling systems, which is referred to as *operational exergy*.

Here, we apply E-LCA to assess two types of data centers. First, we consider a cloud data center with 20,000 servers, which includes corresponding network equipment (switches, routers and cabling) and $N + 1$ redundancy in case of power outage. There is an air-cooling system that has a roughly constant electricity consumption of about 2.75 MW [14]. In this case study, the area floor of the data center is assumed to be 4,645 m^2. The second model is for a medium-scale data center with 185 servers and 567 kW of the total electricity consumption. The medium-scale data center consists of rack mounted servers and an air distribution systems. In the estimation of the embodied exergy, we consider additionally to the rack mounted servers also cables, switches, routers and server cabinets. The main assumptions made for both the cloud center and the medium-scale data center model are listed in Table II .

The *embodied exergy* of the considered large cloud data center with 20,000 enterprise servers, including routers, switches, racks, cabinets and cabling and assuming 40% material reutilization and a lifetime of 9 years, is estimated to be approximately 186 TJ and that of the medium-scale data center to about 2.3 TJ. The manufacturing and assembly phases contribute mostly to the total embodied exergy. For instance, in case of the medium-scale data center, these two phases contribute by approximately 130 TJ, which is more than 70% of the entire embodied exergy consumption. Similarly, an exergy consumption of 1.4 TJ has been calculated for manufacturing and assembly phases of the medium-scale data center, which is approximately 60% of the total embodied exergy.

The *total cumulative exergy* consumption of the large cloud data center, which includes both embodied and operational exergy, was estimated to be about 1.5 PJ without taking into account material reutilization. The corresponding lifetime embodied exergy consumption contributes by about 209 TJ, which is about 14% of the total cumulative exergy consumption. The embodied exergy loss can be reduced to about 186 TJ by reusing 40% of recycled materials and to 145 TJ if 60% of recycled materials are reused. However, the most exergy is consumed during the operational phase, which accounts for about 1.3 PJ or 86% of the total. Hence, the best improvements can be achieved by applying techniques aimed at reducing the energy consumption of data centers.

D. Overall Model

The overall model is depicted in Fig. 2. The main components of the model are briefly described in previous sections. Table III summarizes the life cycle inventory parameters that are used in the presented case study. The embodied exergy consumption (EEC) refers to the sum of exergy consummations of different phases such as raw material extraction, transportation between different phases, manufacturing/assembly and disposal/recycling. For all end-user devices as well as network and processing elements, we define a specific service lifetime. For instance, we assume that a smartphone will be replaced by a new device after 2 years of operation, while a PC is used for 4 years. A longer service lifetime of 9 years is assigned to the network equipment.

TABLE III: *Life-cycle Inventory for Cloud-Computing.*
Notes. EUD: End-User Device, OC: Office Computing, DC: Data Center, AN: Access Network, PC: Power Consumption, EEC: Embodied Exergy Consumption

Devices	Category	EEC [MJ]	PC [W]	Lifetime [Year]	Source
PC includes LCD 15-inch display, mouse and keyoard	EUD/OC	4912	330	4	Analytical/Literature [15,16]
Generic Notebook (15-inch screen)	EUD/OC	1789	55	3	Analytical/Literature [15,16]
ADSL-modem	EUD	170	5	3	Analytical
Generic Smartphone	EUD	803	2.6	2	Analytical/Literature [15,18]
Generic Tablet	EUD	1076	42	2	Analytical/Literature [18]
Enterprise Server	DC/AN/OC	5843	500	3	Analytical/Literature [4]
Rack Switch	DC/OC	3442	638	3	Analytical/Literature [19]
Edge Switch	DC/AN/OC	8410	1500	3	Analytical/Literature [19]
Core Switch	DC/AN/OC	9934	1700	3	Analytical/Literature [19]
NodeB Rack	AN	48503	2370	9	Analytical/Literature [5,7,8]
RNC Rack	AN	33962	2500	9	Analytical/Literature [5,7,8]
SGSN Rack	AN	107483	10500	9	Analytical/Literature [5,7,8]
GGSN Rack	AN	31575	4000	9	Analytical/Literature [5,7,8]
Router(for enterprise and service provider networks in a small form)	DC/AN/OC	5024	400	3	Analytical
Router(Large enterprise, Internet edge, service provider)	DC/AN/OC	6032	1275	3	Analytical
Cable Cat5e (1 m)	EU/DC/AN	6.6	-	-	Analytical/Literature [17]
4-Core optic fibre cable (1 m)	DC/AN/CN	7.6	-	-	Analytical/Literature [17]

TABLE II: *Main assumption made for the E-LCA of data centers*

E-LCA Phases	Cloud Data Center/Medium-Scale Data Center
Raw Material Extraction	Spatial context: Southeast Asia/China Material supply: within a radius of 1000 km 40% of material flows from the recycling phase
Material Transportation	Spatial context: within a radius of 5000 km Mode of transportation: rail/truck
Manufacturing and Assembly	Spatial context: Southeast Asia/China
Product Transportation	From southeast Asia/China to Austria/Vienna Mode of transportation: rail/truck/ship
Operation	Lifespan: 9 years IT equipment maintenance: annually 3% Power usage effectiveness (PUE): 1.1 Redundancy: N+1 Cloud data center with 20,000 enterprise servers Medium-scale data center with 185 enterprise servers input power (cloud data center): 7.75 MW input power (medium-scale data center): 567 kW
End-of-Life Transportation	From northeast Austria/Vienna to Germany Mode of transportation: rail/truck/ship
Recycling	Based on the mass of equipment Approximately 520 kJ/kg exergy consumption [4]

IV. Results and Discussion

The cumulative exergy flow for the model of mobile cloud computing in Austria from 2012 to 2020 is graphically presented in Fig. 3. The figure show the flow of exergy for all phases of the system's life cycle including the raw material extraction, transportation, manufacturing, operation and disposal. The exergy values presented in Fig. 3 include both data centers and network as well as end-user devices of private and business users. In this particular example, 40% of material reutilization is assumed and the total cumulative exergy consumption is estimated to be 222.5 PJ, of which 82.1 PJ (22.8 TWh of electricity) is consumed during the operational phase. Thus, the main part of the total exergy is related to the embodied exergy, which accounts for about 140.5 PJ or 65% of the total. This result is different from the result obtained when considering data centers only, where 86% of the total exergy is consumed during the operational phase. This is because in the overall model, end-user devices contribute significantly to the increase of the embodied exergy due to their high quantity and short service lifetime. On the other hand, material reutilization plays less significant role in reducing the total exergy consumption. The total cumulative exergy consumption assuming 40% material reutilization is 222.5 PJ (see Fig. 3) and in case of 60% reutilization we obtained a value of 216 PJ. With no material reutilization at all, the estimated total exergy loss is 233 PJ. Hence, material reutilization has a moderate saving potential of less than 10%.

The increase of the cumulative exergy consumption over time is shown in Fig. 4. The curves represent five different scenarios assuming: 1) no reuse of recycled materials at all (W/O MR), 2) 40% material reutilization (W/40 MR), 3) 60% material reutilization (W/60 MR), 4) 60% material reutilization and an optimized design of data centers (W/60 MR + Optim.), and 5) 60% material reutilization and increased lifetime of mobile end-user devices to 4 years instead of 2

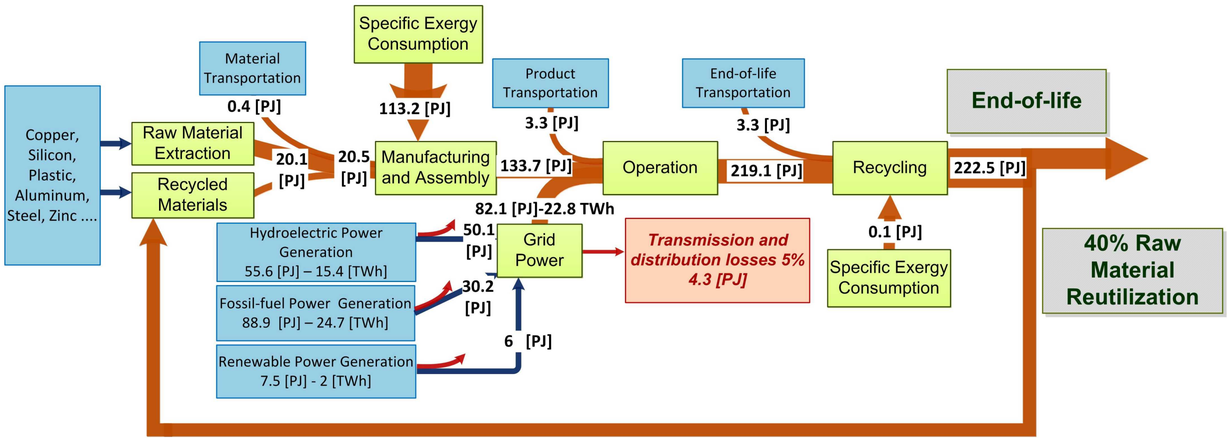

Fig. 3: *E-LCA for mobile cloud computing in Austria from 2012 to 2020. Exergy flow inclusive private and business user devices, data centers, UMTS RAN, and core network and assuming 40% material reutilization*

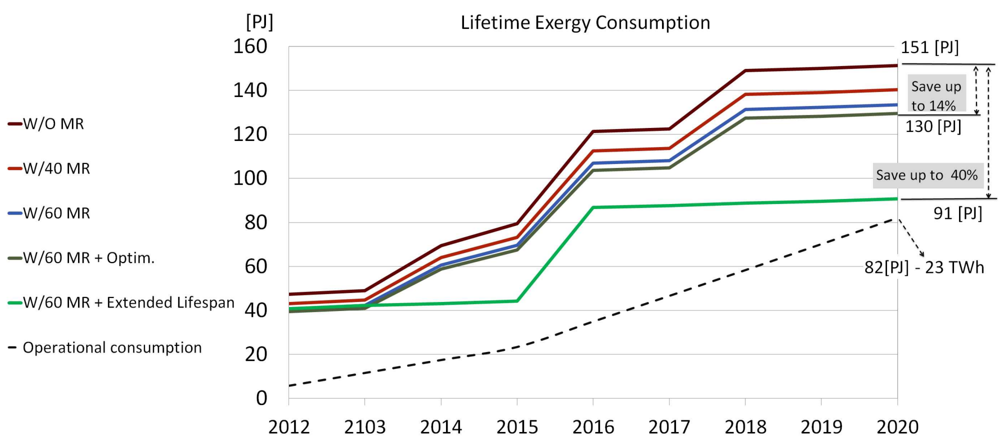

Fig. 4: *Lifetime embodied exergy consumption and savings resulting from network and lifespan optimization W/O MR:without material reuse; W/40 MR:with 40% material reuse; W/60 MR:with 60% material reuse; W/60 MR+Optim.:with 60% material reuse plus optimized core and access network system;W/60 MR+Extended-Lifespan:with 60% material reuse plus two years longer lifetime of end-user devices*

years (W/60 MR + Extended Lifespan). The dashed line in Fig. 4 represents the cumulative lifetime exergy consumption of the operational phase only, i.e. the operational exergy (Operational consumption).

The scenario assuming an optimized design of data centers (scenario 4) refers to the recently proposed method to split system functionality into modular blocks, in order to minimize the amount of material and equipment used, especially around the sheet metal in physical packing [17]. This method called ”dematerialized design” also reduces the size of the printed circuit boards in switches and routers and apply free cooling and an improved data center management. Through an optimized design of data centers, reductions in exergy consumption of more than 50% relative to a baseline scenario are achievable [17].

As already mentioned, material reutilization can lead to moderate savings of the overall lifetime exergy consumption. Even if an optimized data center design according to the above mentioned principles can lead to large savings of the data center related exergy consumption, the achievable savings in the overall exergy consumption are only about 14%.

In order to estimate the impact of the service time of end-user devices on the sustainability of cloud computing, we defined a scenario in which the service time of smartphones and tablets is increased by a factor of two to 4 years. The green line in Fig. 3 represents the results of this scenario (scenario 5). This result illustrates how end-user devices affect the total embodied exergy. Since the contribution of end-user devices to the total embodied exergy is huge, an extension of their service time by a factor of two causes a significant reduction in the embodied exergy, and thus allows savings in the overall exergy consumption of about 40% after 9 years and relative to the case without design optimization and material reutilization.

V. Conclusions

Modern information and communication technologies (ICT), and in particular cloud computing and cloud-related services and applications are affecting our everyday business and social life. They also influence the environment due to the broad use of ICT applications, ICT-related energy consumption and an ever increasing number of electronic devices.

In this paper, we presented an holistic approach based on a combination of the exergy concept and life cycle assessment (LCA), which we applied to study the sustainability of cloud computing on an example of a model made for Austria. Our results have shown that the impact of ICT on the environment grows with time and that there is a potential to slow down this trend. It should be noted that we concentrated here on the impacts related to the life cycle of ICT hardware and not on impacts that result from the change in production, transport, and consumption processes due to the applications of ICT. Nevertheless, the obtained results clearly show the need for a holistic approach that take into consideration the whole system, which includes additionally to data centers also the interconnecting network and end-user devices. Even though an optimized design and management of data centers is an important step towards a sustainable cloud, the huge number of end-user devices and their short service time have much higher impact on the overall system's exergy consumption. It is mainly because end-user devices contribute most to the high embodied exergy consumption that is related to the material extraction, transportation, manufacturing and recycling processes.

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