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SHORT COMMUNICATION

Too expensive to keep — bidding farewell to an iconic mountain glacier?

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Abstract

Humans currently perceive glaciers as icons of a pristine high mountain landscape. Glaciers attract millions of visitors every year and add to building Alpine identity, but also provide ecosystem services. Using Austria's largest glacier as an example, we show that abundant water availability would allow artificial management to conserve the glacier under ongoing climate change, although costs in the order of €10^8 per year exceed threefold related total visitor tourism revenues. While we present a theoretical experiment that due to economic reasons most likely never will be realized, we quantify (un-)feasibility and discuss potential environmental constraints.

Keywords Glaciers · Glacier tourism · Climate change

Introduction

Glaciers have an important role in mountain environments and as ecosystem service providers to downstream communities worldwide, in particular by supplying significant amounts of water and compensating low-flow through ice melt in summer (van Tiel et al. 2020). The relevance of this effect depends on the climatological setting (Kaser et al. 2010) and the amount of glacier coverage, which both are changing and will continue to change in future (Huss and Hock 2018). While ice melt impacts the hydrological cycle across scales, locally glaciers bear a socio-economic role as a tourist attraction (e.g., Welling et al. 2015; Purdie 2013) and a brick in identity-building.

On Pasterze glacier (PG), Austria's largest glacier (15 km^2), around 1 million visitors come per year using an access road built in 1935. The number of visitors has been stable over recent decades (Grossglockner Bergbahnen Touristik GmbH 2020). A main motivation of the vast majority of tourists for the visit is seeing (and "touching") a glacier (Unger 1989), potentially enhanced by some "last chance tourism" (Salim and Ravanel 2020) in recent years. Such high visitor numbers are remarkable and also owed to excellent accessibility of PG, as often visiting glaciated areas is restricted to a small group of experts or people with niche interests such as mountaineering. Strong glacier recession (Fig. 1) and the fear of disappearance of glaciers previously thought to be "Eternal Ice" have triggered an unprecedented focus on their fate raising the question of their societal and even the economic value. Glaciers cannot be preserved in their current extent and recent figures from the Alps point towards a strong reduction in volume during the remainder of the twenty-first century. This is true regardless of the emission scenario to come due to a significant committed volume loss as a consequence of existing disequilibrium (Zekollari et al. 2019). On single glaciers however, technical measures can be considered in order to reduce ablation (Huss et al. 2021). This can include the protection of neuralgic zones through coverage with textiles (Olefs and Fischer 2008) or increased artificial snow (AS) production (Hartl et al. 2018). It has been shown that the latter could reduce local ice melt significantly (Wang et al. 2020). A detailed modeling and feasibility study at Morteratsch Glacier in

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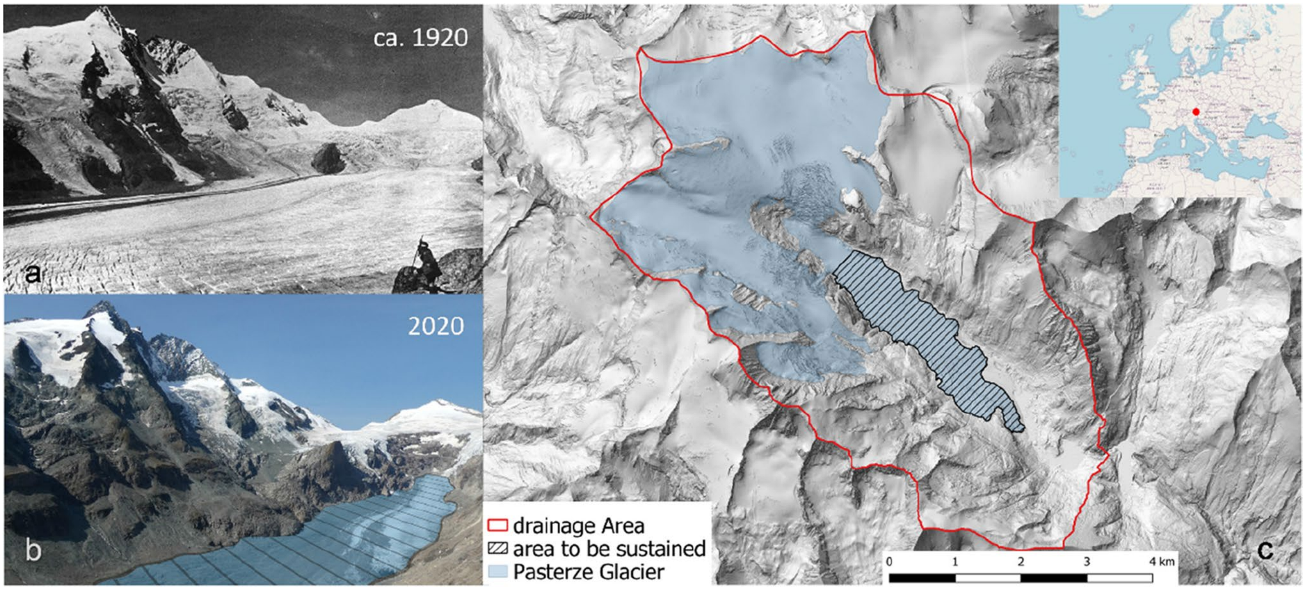

Fig. 1 **a** PG around 1920 (archive G. Lieb); **b** PG in September 2020 (photo: G. Lieb) — the approximate area used for the model calculation is marked in blue; **c** map of PG with the area used for the model calculation dashed and its location in Europe (inset)

Switzerland (Oerlemans et al. 2017) aims at building the basis for an implementation of a glacier conservation experiment; however, this has not yet been implemented (Mortalive, 2021).

Data and methods

We apply a one-dimensional hydrometeorological surface energy balance model (Theurl 2020) with data from an automated weather station (AWS) in the lower ablation area of PG (47°05′N; 12°43′E; 2110 m a.s.l.) between 2012 and 2019 that we aggregate from hourly to daily values. The turbulent fluxes are determined based on a bulk approach. Roughness lengths differ depending on the surface type (snow: 0.001 m or ice: 0.002 m), which we infer from the measured surface elevation changes and albedo. We validate the model with measured ablation at the AWS and obtain a good representation of reality (Pearson Correlation Coefficient: 0.94). Produced melt water results in runoff.

In order to obtain spatial atmospheric fields as spatial model input, we apply constant vertical gradients of air temperature (0.0065 K/m) and air pressure (0.12 hPa/m) to the AWS data using a digital elevation model (DEM) of 2012 of 10 m grid size. Precipitation gradients are scaled applying a linear regression (Leidinger 2013, Tab. 7.2) that has been empirically derived for the Sonnblick area less than 20 km away from PG. Since we model the glacier tongue only and hence a modest elevation range of around 300 m, we argue that vertical gradients are of lesser importance for other atmospheric variables, which is why we keep humidity and wind speed constant over the model domain of the lower PG tongue. Spatial heterogeneity exists in shortwave incoming radiation. We assess daily potential radiation values for the 30-m grid and build a ratio of the daily mean measured incoming shortwave radiation of a given day at the AWS with the respective potential incoming shortwave radiation. We apply this ratio to the grid of potential radiation for the study area and thus obtain a spatial field of daily shortwave incoming radiation.

The amount of AS needed to reach neutral balance at the end of the balance year is estimated by running the model iteratively with the extrapolated atmospheric fields averaged for 25 m elevation bands for reasons of computational efficiency. Mass input (through AS) and hence, the shortwave reflected radiation is altered due to the changed surface type (fresh snow) whenever atmospheric conditions allow AS (wet-bulb temperature $< = -2$ °C following Hartl et al. (2018)). The total annual AS production volume is converted to water equivalent (w.e.). The model is coded in Python and its details are documented in the code, which can be freely accessed (Theurl 2020).

An important constraint of the results is that glacier dynamics in principle affect surface changes in addition to mass balance by emergence or submergence velocities. In the ablation zone, upward ice flux (emergence) compensates height changes of the glacier surface due to ablation to some extent. We neglect surface elevation changes due to ice dynamics and argue that this does not affect the results significantly due to the following: We base our study on a rather short study period of 8 years, which limits the amount of ice advected through emergence, given that Hynek et al. (2019) report emergence velocities in the order of below 0.5 m/yr. This is one order of magnitude lower than the observed ablation values (typically between – 3 and – 9 m w.e. per year in the ablation zone). The low emergence velocity values are related to a dynamic decoupling of the ablation zone from the accumulation zone, which are only connected through a narrow ice band where little ice volume gets transported through. This simplification would lose validity if the experiment would not only create a neutral (i.e., ablation is compensated by accumulation) but also positive mass balance.

We include both debris and debris-free areas of the tongue for our assessment as our hypothetical experiment thrives to sustain PG as it is now. The strong proglacial landscape changes at PG imply increased debris-covered and dead ice at PG (Avian et al. 2018). We argue that while there may be ice stored for much more time to come, it will not be of touristic value as the untrained visitor will not perceive it as a glacier surface.

The costs associated with this hypothetic AS production — including capital costs, maintenance and staff, water as well as energy costs for the electricity used in water pumping, and air compression — are estimated to be around 3.3 €/m^3 (Cognard and François 2015).

On tourist expenditure, we use the average daily expenses per tourist for the year 2013/14, building on an average of €152 in winter and €125 in summer (WKO 2016) — for our purpose assuming 80% of the tourists coming during summer, as the High Alpine road is closed for much of the winter. For the toll for the High Alpine road, which accounts for €37 for cars (Grossglockner Hochalpenstraße AG 2020), we assume an occupancy rate of 2 passengers per car.

For the greenhouse gas footprint of current tourism transport, we combine vehicle arrivals in 2019 (186 931 cars, 3986 buses, and trucks for tourism service goods supply), the minimal distance from nearby Heiligenblut to PG and back (32 km) and 2019 emission factors (Umweltbundesamt 2019) with the upper bound of the share of visitors attracted by PG (20%).

Results and discussion

We quantify that an annual AS production of between 2.4×10^7 m^3 and 3.6×10^7 m^3 would have been necessary to have kept the tongue of PG in balance in the hydrological years (1 October to 30 September) 2012/2013–2017/2018 (Table 1). The spatial distribution of AS production is rather similar each year at a relative scale (Fig. 2), while absolute values vary strongly depending on how far the glacier balance (without AS production) deviates from neutral conditions (conditions where accumulation balances ablation over a year). Comparing for instance the year 2013/2014 (a year with favorable conditions for the glacier) with 2014/2015 shows that ASP can differ by more than 2 m w.e.

On the feasibility of keeping a neutral balance of the glacier tongue, both the water demand and the economic costs have to be considered. Since the water amount necessary for neutral balance is very high (Table 1), we attempt a rough estimate of the fraction of the catchment's precipitation that would represent the water volume necessary. Average annual precipitation in the Pasterze catchment between 1981 and 2010 was 1496 mm (Hiebl and Frei 2018). For a total catchment area of PG of 33.7 km^2 (Geilhausen et al. 2012), we hence obtain an annual available water mass of 5.0×10^{10} kg in the catchment. The average AS production volume necessary to achieve neutral balance over a year would be 3.1×10^7 m^3 (Table 1), which corresponds to 1.4×10^{10} kg of water assuming a snow density of 450 kg/m^3 (Rogstam and Dahlberg 2011). As such, roughly 29% of the annual precipitation in the entire catchment would need to be converted into AS in order to achieve neutral balance. We use precipitation to relate AS production to water availability and not catchment discharge as the latter is not measured consistently over the study period and furthermore is influenced by changing glacier conditions. This would be in conflict with our precondition of the experiment (i.e., keeping an unchanged geometry). Hence, from a water availability perspective, the experiment of keeping the PG tongue in its current shape would be possible in principle.

Table 1 Required artificial snow (AS) volume [m^3] assuming a snow density of 450 kg/m^3, specific annual AS production for the area defined in Fig. 1 at PG's tongue (2.3 km^2) and production costs required in order to obtain neutral balance for each hydrological year (October to September) in Million € calculated for average production costs of 3.3 €/m^3

Hydrological year	Annual AS production volume [m^3]	Specific annual AS production [m water equivalent]	Annual costs for AS production [million €]
2012/2013	2.92×10^7	5.7	96.2
2013/2014	2.43×10^7	4.8	80.2
2014/2015	3.63×10^7	7.1	119.7
2016/2017	3.31×10^7	6.5	109.4
2017/2018	3.48×10^7	6.8	114.8
2018/2019	3.43×10^7	6.7	113.3

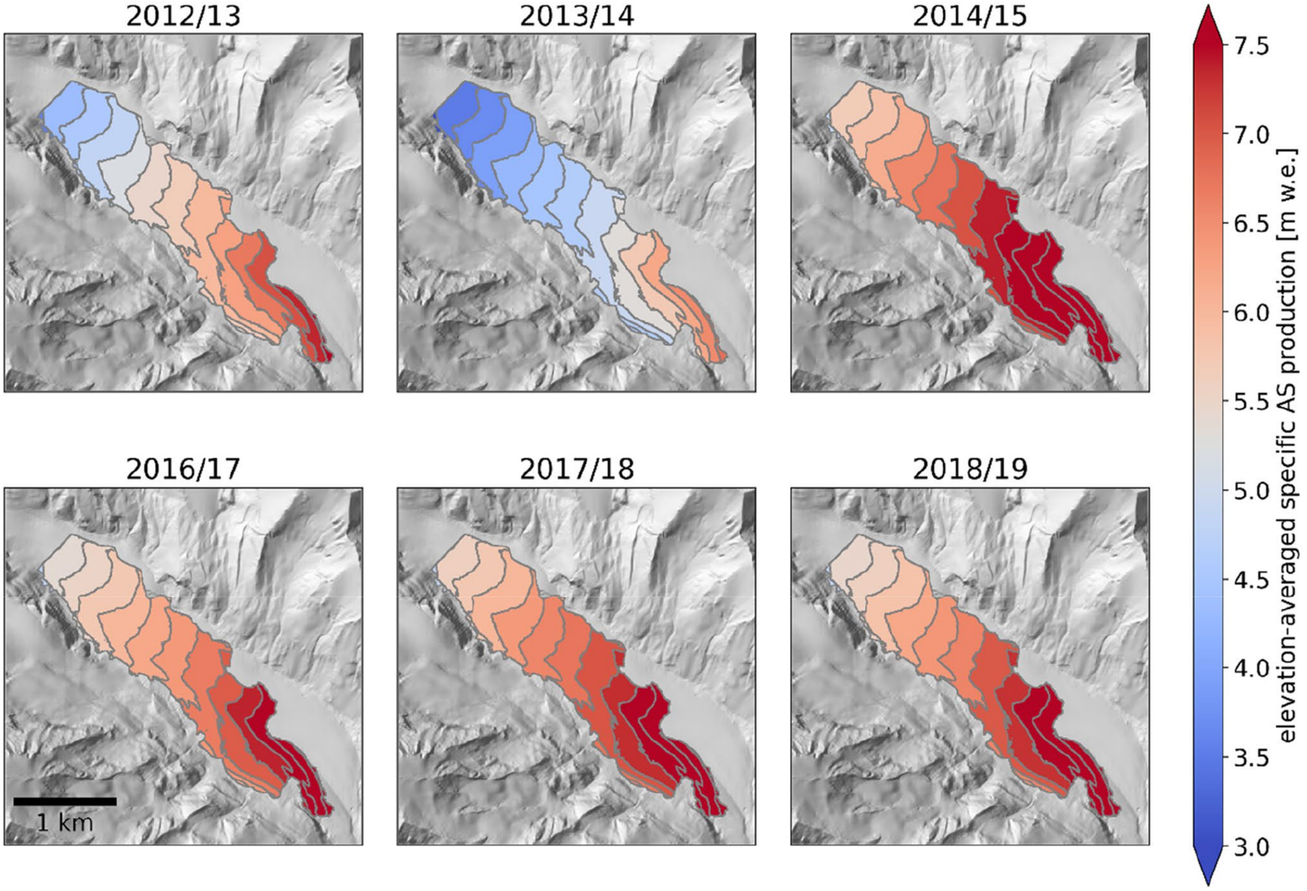

Fig. 2 Spatial distribution of specific artifical snow (AS) production necessary to obtain neutral balance for the years 2012–2018. Note that 2015 was excluded due to a data gap of several months from the automated weather station (AWS)

Necessary snow amounts would exceed the above by far in case a glacier was to be formed on bare rock (without the existing glacier in place). This is due to the fact that in such a case the maximum surface temperature could exceed 0°C and freshly produced snow would more likely melt away.

The costs, however, are significant: Snow volumes required per year translate to economic costs in the order of €100 million per year. We relate this to the value added that can be attributed to glacier tourism at PG. Based on surveys and questionnaires (Unger 1989), we estimate a share of 3 to 20% of the arrivals that are attracted primarily by PG (overall 807,333 arrivals in 2019 (Grossglockner Bergbahnen Touristik GmbH 2020)). Taking into account the travel time for a visit to PG, visitors will stay on average for an extra day and consequently, we can account for an average value added of approximately €150 per visitor (covering both the average daily expenses per tourist and the toll for the High Alpine road). The annual value added foregone due to complete glacier loss would then range between €3.6 million (for 3% share of overall visitors attracted by PG) and €24.2 million (for 20%). Additional losses are probable to occur when the PG retreats further or disappears entirely as this may lead to diminishing numbers of hikers and climbers in the region as a result of a decline in scenic beauty and attractiveness (Wang and Zhou 2019). Furthermore, increasing risks including rockfall, unsafe trail construction and prolonged hiking times due to the melting of the glacier tongue (Pröbstl-Haider et al. 2016) may reduce tourist attraction significantly.

Assessing the maintenance of the PG in its current shape from a solely economic viewpoint, the costs of AS production (€106 million per year on average) might be interpreted as preventive costs to mitigate the negative impacts of climate change in order to keep the attractiveness for tourism. If we relate this cost to the 20% of current annual tourist arrivals that were identified as rather the upper bound of being primarily attracted by PG, the preventive costs amount to approximately €656 per tourist arrival. Evidently, in a future scenario where most Alpine glaciers will have disappeared the attractiveness of the few remaining glaciers will increase, lowering the (preventive) cost ratio per tourist. Yet further warming will also increase the demands on AS production and the related costs. Thus, only if it would be an (almost) single and very favored attraction could the cost allocation per tourist decline, but given its current level of at least €656 per tourist (and possibly a multiple of that), this still might not be an attractive option considering the average value added gained per tourist to be around €150 as established above.

For comparison, adaptation in related or other areas to date mainly concern options where the additional costs are only a fraction of supply costs without adaptation. For example, in the early 2010s, AS production in a typical alpine ski resort required costs at the level of €3.5 per skier day (Damm et al., 2014). In addressing increased flooding risk due to climate change, the costs for dry-floodproofing of buildings — using the example of Venice Beach in Los Angeles and Naples in Long Beach — are between 9500 and 18,000 US$ per building at the 2010 price level (de Ruig et al., 2020), representing a small fraction of the infrastructure cost itself. For those few cases where — mainly expected for the future — additional costs might come close to supply costs without adaptation, they will not exceed the latter by a multiple. For example, in a case study in the Alps, the required rise in real ski lift ticket prices to balance increasing snow production costs under ongoing climate change and considering projected declining visitor numbers was found to be 2.5% per year up to the mid-twenty-first century (Damm et al., 2014). In a dynamic perspective, these other areas adaptation is already applied and technologies usually can benefit from economies of scale due to wide-spread application. This will not be the case for avoiding glacier retreat (specifically beyond AS production itself), which will remain restricted at best to very few applications as it is not meeting a basic need. Covering the costs of avoiding glacier retreat will be limited by respective demand (basically willingness to pay for glacier tourism). To ensure high enough willingness to pay at any specific site, the number of such locations needs to be restricted to very few. It is an open question whether demand will be high enough to cover the significant costs for one or a few locations at all. In mitigation applications, costs may initially be multiples but with learning from broad applications, later on, the costs come down to at most a fraction or turn even negative, with the clean technology cheaper than the initial fossil one.

Other examples of large (infrastructure) investment now attracting tourists have often been initially installed for other purposes, for instance, in relation to general economic development (such as the Caledonian Canal in Scotland for shortening sailing shipping distances for the British Empire, which opened in 1822 and is now available for tourist boating) or for military purposes (such as the Dolomite railway during World War I which was later transformed into a bike trail). The authors are not aware of any large investments for tourism itself at costs exceeding the respective foreseen willingness to pay for its use. In terms of ecological impacts, under current transport technology, the greenhouse gas transport footprint of PG tourism at its recent scale is in the range of 220 t CO_2eq per year.

The glacier surface covered with AS would — at least during the artificial snowing season — look like a snowfield. From our experience, we conclude that tourists infer from the directly witnessed surface, snow, with their knowledge of the massive ice mass below to observe a glacier. This fascination goes beyond the already high attractiveness of experiencing snow itself, which is enhanced due to its exoticism in particular in the summer season.

PG is by far not the only glacier attraction in the Alps (Salim et al. 2021) and one could consider other sites that may be easier to sustain. However, direct accessibility from a (high alpine) road and the connection to an otherwise attractive tourist route (e.g., connecting the city of Salzburg with many interesting tourist destinations in Southern Austria or even Italy) results in both exceptionally high visitor numbers and — partly related — in an outstanding symbolic function of PG after more than a century of glacier tourism. PG has become the most prominent example for glacier visits in the Eastern Alps. But even in the Western Alps, those of best accessibility often reach lower altitudes than PG but do not reach the same number of visitors. For example, an objectively more favorable site, the Mer de Glace (North exposed, glacier margin reaching down to ca. 1900 m a.s.l.), is accessible from the tourist resort Chamonix by a cog railway but has less than half the number of tourists than PG (Salim and Ravanel 2020). In case further attractive sites will emerge or are considered to be developed, the method as applied here for PG would need to take care of their local specifics. An important climatological condition to assess would be the deviation of a specific glacier from the current state to an equilibrium state. Valley glaciers such as the PG have their lower glacier tongues in elevations that can be considered as relic of past climate conditions and hence in principle are particularly difficult to sustain. Other issues to be assessed include accessibility, exposition, and ecological constraints. In future research, it would be particularly interesting to analyze glaciers, their tourism potential, and the feasibility to sustain them in other climate zones. While some sites in North America (Glacier Bay National Park, Alaska) or New Zealand (West Coast Glacier region) attract lower visitor numbers than PG, glacier tourism is signifcantly more relevant in other North American glacier sites (Glacier National Park received on the order of 3 million visitors between 2016 and 2019 (IRMA 2021)). In China, glacier tourism reaches much higher numbers with more than 5 million visitors at Yulong Snow Mount and Gongga Snow Mount (Wang and Zhou 2019).

Conclusions

We present the results of an interdisciplinary approach quantifying climate change mitigation feasibility and hypothetical costs by applying a state-of-the-art surface energy balance model to PG. We find that current water availability would be sufficient to produce enough AS in order to keep a neutral glacier mass balance, while the associated costs exceed economic feasibility by far. This is true for current climate conditions and will therefore be even more applicable in the future, since stronger snow and ice ablation needs to be compensated for. The estimated economic costs may be regarded as a lower limit if we consider PG to be carrying a symbolic as well as an intergenerational value. Our results show that the tipping point of feasibility of keeping the PG in its current shape as a tourist attraction has already passed. In addition to the economic constraints of such a project, environmental and logistical issues regarding building the necessary infrastructure for water supply and distribution over the glacier would need to be considered if it was to become reality. In the case of PG, other legal and environmental aspects include the location of the glacier, not only in the core zone of a national park (IUCN category II) but even within its special protection zone. This would impact local ecosystems as well as the artifical change in the water regime (strength and timing of the precipitation buffer function) for downstream ecosystems and human use. Most of the issues raised would add onto the complexity for the realization of such a project beyond economic constraints, which emphasizes the hypothetical nature of it.

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Author contributions Jakob Abermann, Wolfgang Schöner, and Karl Steininger conceived the study. Manuel Theurl performed SEB simulations and Elisabeth Frei and Karl Steininger performed the economic assessment. Bernhard Hynek provided validation data. Jakob Abermann wrote the manuscript with input from all co-authors.

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Data availability The data and materials are available on request from the authors.

Declarations

Ethics approval Approved by all authors.

Consent to participate Consented by all authors.

Consent for publication Consented by all authors.

Competing interests The authors declare no competing interests.

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