SUPPLEMENTARY INFORMATION

Predicting climate change impacts on polar bear litter size

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Summary of Supplementary Information

Supplementary Methods. Derivation and parameterization of the dynamic energy budget model for adult female polar bears without dependent offspring. The model tracks changes in storage energy (and thus also body mass and energy density) over time due to energy intake (feeding) and expenditure (somatic maintenance, movement), and was used to predict the energy density of pregnant females at den entry as a function of on-shore arrival date.

Supplementary Note. Discussion and sensitivity analysis of the reproduction threshold parameterization. We discuss whether and how our simplifying assumption of a minimum threshold for reproduction may affect predictions of future litter size.

Supplementary Figure S1. Sensitivity of litter size predictions to choice of reproduction threshold $\varepsilon_{\text{min}}$. The figure shows detailed predictions of litter size as a function of on-shore arrival date when using a reproduction threshold of $\varepsilon_{\text{min}} = 18.0 \text{ MJ kg}^{-1}$ instead of $\varepsilon_{\text{min}} = 20.0 \text{ MJ kg}^{-1}$.

Supplementary Figure S2. Sensitivity of litter size predictions to choice of $\varepsilon_{\text{min}}$ when controlling for the dependency of the August 1 initial condition on $\varepsilon_{\text{min}}$. The figure shows the sensitivity of mean litter size predictions to changes in $\varepsilon_{\text{min}}$, using reproduction thresholds from 14.0 MJ kg$^{-1}$ to 22.0 MJ kg$^{-1}$.

Supplementary References.
Supplementary Methods.

Derivation and parameterization of the dynamic energy budget model for adult female polar bears without dependent offspring.

Here, we develop and parameterize the dynamic energy budget (DEB) model that was used to estimate changes in body mass, storage energy and energy density of adult female polar bears without dependent offspring during summer and fall (June through September). The model is based on the body composition model of ref. 29, and tracks changes in storage energy (and thus also changes in body mass and energy density) over time due to energy intake (feeding) and expenditure (somatic maintenance, movement). For bears fasting and resting on shore, the model is equivalent to the DEB model for fasting, resting, non-growing and non-reproducing polar bears in a thermoneutral state, presented in ref. 29. For bears feeding on the sea ice (Late Feeding scenario only), the model also accounts for changes in storage energy due to feeding and movement. In both cases, the model assumes that no energy is allocated to thermoregulation (due to good insulation, and mild summer and fall temperatures61), structural growth (because we only consider reproductively active females at least 4.5 years old, and females in western Hudson Bay have usually completed structural growth before that age46), or reproduction (because blastocyst implantation in polar bears only occurs at, or shortly before, den entry26).

The model also assumes strong homeostasis28,29 throughout. Although this assumption is supported by recent body composition analyses of fasting polar bears25,29,62, it is also conceivable that, at least at some point during the fast, polar bears preferentially catabolize storage fat before using storage protein as an energy source63,64. However, in this latter case, maintenance requirements would drop slower over time than with strong homeostasis (because somatic maintenance rate depends on lean body mass but not on body fat29), so that more storage energy would be used to ensure survival and less storage energy would remain for reproduction. This effect would become more pronounced with increasing fasting period length, rendering our predictions of future litter size, obtained under the assumption of strong homeostasis, conservative. Litter size predictions may further be considered conservative if environmental changes result in increased energy expenditure.
towards locating, excavating or maintaining suitable maternity dens\textsuperscript{6,65} (i.e., if climatic warming results in a violation of our assumption of negligible on-land movement, cf. below).

\textit{Derivation of the DEB model}

All tissue of a polar bear can be characterized as structure or storage\textsuperscript{29}. Storage encompasses all materials that can be used as an energy source for maintenance, movement, growth and reproduction (e.g., non-structural lipids and proteins), plus body water and ash associated with these materials. Structure consists of any remaining tissue, body water and ash, and cannot be utilized for energy even under extreme starvation (e.g., bones, brain, lungs, etc.). Here, we only consider adult (i.e., fully grown) bears, which implies (together with our assumption of strong homeostasis) that structural mass (which can be estimated from straight-line body length\textsuperscript{29}) remains constant over time\textsuperscript{29}. Storage mass, however, fluctuates with energy intake and expenditure.

Due to the assumption of strong homeostasis the rate of change in storage energy, $E$, can be represented by a single differential equation:

\begin{equation}
\frac{dE}{dt} = F_{\text{IE}} - F_{\text{EM}} - F_{\text{ES}},
\end{equation}

where $F_{\text{IE}}$ represents the influx of energy through food acquisition and assimilation, and $F_{\text{EM}}$ and $F_{\text{ES}}$ represent the respective rates at which storage energy is utilized for movement and somatic maintenance. Because we only consider adult females without dependent offspring during summer and fall, no energy is allocated to thermoregulation, growth, or reproduction. The functional forms for the fluxes $F_{\text{IE}}, F_{\text{EM}}$, and $F_{\text{ES}}$ were specified as follows:

Somatic maintenance rate ($F_{\text{ES}}$) depends on body composition because maintenance requirements of body fat are negligible relative to those of lean tissue\textsuperscript{29,66,67}. We therefore followed ref. 29 in assuming that $F_{\text{ES}}$ is proportional to lean body mass (i.e., the mass of all tissue that is not body fat), $LBM$, and we used their body composition model to re-write $LBM$ as a function of storage energy and straight-line body length, $L$:
where \( \alpha \) represents the energy density of storage, \( \varphi \) is the proportion of storage mass that is fat, and \( \rho_{\text{STR}} \cdot k \) is a composite proportionality constant needed to estimate structural mass from straight-line body length. Somatic maintenance rate therefore becomes

\[
F_{\text{ES}} = m \cdot \left( \rho_{\text{STR}} \cdot k \cdot L^3 + \alpha^{-1} \cdot (1 - \varphi) \cdot E \right), \quad (S3)
\]

where metabolic rate, \( m \), is the energy required per unit time to maintain a unit mass of lean tissue\(^{29}\). Equation (S3) is equivalent to the formula for \( F_{\text{ES}} \) provided in ref. 29 but here we have explicitly re-written \( F_{\text{ES}} \) as a function of storage energy (rather than body mass), which becomes more convenient in the present context.

In contrast to somatic maintenance, energy costs of movement depend on total body mass, \( M \), because both lean tissue and body fat need to be moved. The rate at which storage energy is utilized for movement (\( F_{\text{EM}} \)) can be described by an allometric equation of the form

\[
F_{\text{EM}} = aM^b + cM^d \cdot v, \quad (S4)
\]

where \( v \) represents velocity\(^{55,68,69}\). The first part of the sum, \( aM^b \), represents the metabolic costs of maintaining posture during locomotion (in addition to somatic maintenance)\(^{70,71}\). The second part, \( cM^d \cdot v \), reflects the positive linear relationship between energy consumption and velocity. This linearity has been demonstrated for a wide variety of animals\(^{55,68,69}\), including polar bears for the range of velocities encountered in the wild\(^{53,54}\).

Body mass (\( M \)) can also be re-written as a function of storage energy and straight-line body length\(^{29}\),

\[
M = \frac{\rho_{\text{STR}} \cdot k \cdot L^3}{\text{Structural mass}} + \frac{\alpha^{-1} \cdot E}{\text{Storage mass}}, \quad (S5)
\]

so that the rate of storage energy allocation towards movement becomes
\[ F_{EM} = a \cdot (\rho_{STR} k L^3 + \alpha^{-1} E)^b + c \cdot (\rho_{STR} k L^3 + \alpha^{-1} E)^d \cdot v. \] \hspace{1cm} (S6)

The rate of energy intake \((F_{IE})\) is often modelled as size-dependent within the dynamic energy budget framework\textsuperscript{28,31}, but no evidence exists for size-dependent feeding in adult polar bears. Therefore, in absence of evidence to the contrary, we opted for the most parsimonious model, assuming size-independent and constant feeding at rate \(\beta\). After accounting for digestive efficiency \(\delta\), the rate of energy intake becomes:

\[ F_{IE} = \delta \beta. \] \hspace{1cm} (S7)

In sum, the rate of change in storage energy is given by the following differential equation:

\[
\frac{dE}{dt} = \delta \beta - \left( a \cdot (\rho_{STR} k L^3 + \alpha^{-1} E)^b + c \cdot (\rho_{STR} k L^3 + \alpha^{-1} E)^d \cdot v \right)_{\text{Feeding}} \nonumber \\
- \left( m \cdot (\rho_{STR} k L^3 + \alpha^{-1}(1 - \varphi) \cdot E) \right)_{\text{Somatic maintenance}} 
\], \hspace{1cm} (S8)

which can be integrated numerically to give storage energy as a function of time, \(E(t)\), for a bear of given straight-line body length \(L\) and initial energy stores \(E(0)=E_0\).

The dynamics of total body mass \((M)\) and energy density \((E/LBM)\) are also fully described by equation (S8) because storage energy \((E)\) can be converted into total body mass using equation (S5) and into energy density with equation (S2), i.e.

\[ E / LBM = \frac{E}{\rho_{STR} k L^3 + (1 - \varphi) \cdot \alpha^{-1} E}. \] \hspace{1cm} (S9)
In the present context, equation (S8) in combination with (S5) was used to project storage energy (and thus body mass) backwards in time for the Late Feeding scenario to obtain the body mass of females \( t \) days before on-shore arrival \( (M(t_0-t)) \), given body mass at on-shore arrival \( (M(t_0)=M_A) \), cf. Methods. For body mass projections on-shore [(i) projections forward in time from \( M(t_0-t) \) to obtain body mass, storage energy and energy density at den entry; (ii) scaling of body mass data from capture date to the reference on-shore arrival (August 1) and den entry (October 1) dates], we assumed negligible feeding and movement (i.e., \( \beta = 0, a = 0, v = 0 \), see below). In this case, model (S8) is equivalent to the DEB model for fasting, resting, non-growing and non-reproducing polar bears in a thermoneutral state in ref. 29, which can be solved analytically to estimate body mass, storage energy and energy density changes over time using the mass loss curve of ref. 29.

**Parameterization of the DEB model** (cf. also Table 2 for a summary of parameter definitions and parameter estimates)

The body composition parameters \( \alpha, \varphi \) and \( \rho_{STR \cdot k} \) determine the relationships between total body mass, storage energy and energy density [equations (S2), (S5), (S9)], and they thus also determine the rate at which energy is allocated to somatic maintenance [equation (S3)]. Considering adult females only, we used the sex- and age-class specific means of these parameters\(^{29}\), setting \( \varphi = 0.627, \alpha = 26.14 \text{ MJ kg}^{-1}, \) and \( \rho_{STR \cdot k} = 14.94 \text{ kg m}^{-3} \). Metabolic rate \( (m) \) was set equal to the mean value previously estimated for adult males\(^{29}\), \( m = 0.089 \text{ MJ kg}^{-1} \text{ d}^{-1} \), because \( m \) refers only to somatic maintenance rate of lean tissue, and sex-specific differences in body composition are already accounted for through the parameters \( \alpha \) and \( \varphi \)\(^{29}\).

Model parameters describing the energetic costs of movement were derived by re-examining oxygen consumption data\(^{53,54} \) of two 4 year old polar bears that were trained to walk on a treadmill at velocities ranging from 1.8 km h\(^{-1} \) to 7.2 km h\(^{-1} \). The linear regressions between oxygen consumption and walking speed reported for these bears\(^{53,54} \) yielded no evidence for a postural effect, because the \( y \)-intercepts were at or below basal metabolic rate. We therefore assumed that any postural effect in polar bears would be negligible, and set \( a = 0 \). The mean slope of the two reported regressions (i.e., the incremental cost of
locomotion, \( c \) was twice as high as expected for other species of comparable size (as determined from the interspecific allometric curve in ref. 55), so we set \( c = 0.0214 \) MJ km\(^{-1}\), twice the value in the allometric curve of ref. 55. The treadmill data were insufficient to determine the exponent \( d \) specifically for polar bears, so we set \( d = 0.684 \), in accordance with the interspecific allometric curve\(^{55}\). The average velocity for females moving and feeding on the sea ice was set as \( v = 5.6 \) km d\(^{-1}\) \(^{56}\). After on-shore arrival, we assumed negligible movement\(^{56,57}\), setting \( v = 0 \).

On-ice feeding rates (\( \beta \)) are not documented for polar bears in Hudson Bay, so we approximated \( \beta \) by assuming a diet consisting only of ringed seals (\( Pusa hispida \))\(^{72}\) and setting capture rates and age-composition of kills to the average values reported for the High Arctic during the months of June and July\(^{35}\). Of the two sets of calorific values reported for individual seals in ref. 35, we used the (more conservative) regression values which Stirling & Øritsland derived from the literature (ref. 35, p. 2604). We further corrected energy acquisition downwards by assuming that 20\% of any given kill is not eaten\(^{58,59}\), arriving at an average feeding rate \( \beta = 59.1 \) MJ d\(^{-1}\). Digestive efficiency was set as \( \delta = 0.917 \), assuming a mixed diet consisting of both fat and protein\(^{60}\). After on-shore arrival, we assumed that any energy intake from terrestrial food sources is insignificant\(^{22-24}\), setting \( \beta = 0 \).

It should be noted that the feeding rates reported for the High Arctic\(^{35}\), used in our approximation of \( \beta \), probably overestimate June and July feeding rates of at least some polar bears in western Hudson Bay. Assuming these feeding rates and energy utilization for movement as outlined above, backwards projection of August 1 body masses (\( M_A \)) to June 1 (cf. Methods) results in body mass falling below structural mass for one of the 40 sampled females, which is physiologically impossible\(^{29}\). Projected June 1 body mass also falls close to structural mass for some other females (e.g., within 25\% of structural mass in four, and within 50\% of structural mass in seven other females), indicating that their feeding rates were probably overestimated, or that their energy utilization was underestimated. Net energy intake (the difference between energy intake through feeding and energy utilized for movement) would be overestimated in either case. The Late Feeding scenario therefore probably overestimates the energetic impact of earlier on-shore arrival because the actual loss of energy intake due to shortened on-ice feeding is likely smaller than assumed.
Supplementary Note
Discussion and sensitivity analysis of the reproduction threshold parameterization

In our analyses of litter size, we used multinomial logistic regression to estimate the probabilities of having one, two or three cubs at den emergence \((p_1, p_2, p_3)\) as a function of maternal energy density at den entry. These analyses were based on data from females that were captured twice, once in fall before den entry and then again in spring at den emergence. Females with insufficient storage energy for denning survival, gestation and lactation do not enter maternity dens and leave the denning area before early spring when re-sampling occurs\textsuperscript{25,26}. Re-capture data on non-reproducing females, necessary to confirm reproductive failure, were thus unavailable to be included in the regression analyses, and the probability function of having zero cubs \((p_0)\) could therefore not be determined together with \(p_1, p_2\) and \(p_3\). Instead, to fully describe the relationship between energy density and litter size, we assumed a reproduction threshold\textsuperscript{31,32}, \(\varepsilon_{\text{min}}\), defined such that females produce at least one cub if their energy density is above the threshold on October 1, whereas below the threshold they cannot reproduce. The threshold was chosen as \(\varepsilon_{\text{min}} = 20.0\) MJ kg\(^{-1}\), the lowest den entry energy density ever observed for a female that produced at least one cub\textsuperscript{26}.

The existence of such a reproduction threshold is supported by dynamic energy budget theory\textsuperscript{52} and in accordance with the energetic requirements of maternity denning\textsuperscript{25,26}. However, some variation in the precise value of the threshold is likely to exist between individuals, and such variation would imply a more continuous transition between 'reproducing' and 'not reproducing' than assumed here. Some females may be able to reproduce despite being below \(\varepsilon_{\text{min}}\) on October 1, but such cases may have gone undetected in the past. By contrast, it is also possible that some females above \(\varepsilon_{\text{min}}\) do not produce a litter, and such cases may also have gone undetected due to the lack of data on non-reproducing females. Because we have parameterized \(\varepsilon_{\text{min}}\) using the lowest den entry energy density ever observed in a reproducing female, and because this estimate emanates from long-term (>40 years) observations in western Hudson Bay (and thus a much larger sample size than used in our regression analyses)\textsuperscript{6,26}, we suspect that the number of non-reproducing females above \(\varepsilon_{\text{min}}\) either balances or outweighs the number of reproducing females below \(\varepsilon_{\text{min}}\). This would imply that our assumption and parameterization of a fixed reproduction threshold would
overestimate population reproduction, rendering our predictions of future changes in litter size conservative. However, in the absence of new data on non-reproducing females that would also allow estimating $p_0$ by regression, we cannot discard the possibility that a lower estimate of $\epsilon_{\text{min}}$ may approximate polar bear reproduction better (i.e., that we may have underestimated population reproduction). To understand how this case would affect our litter size predictions, we next repeat our analyses with a reproduction threshold that is 10% lower than previously assumed, that is, $\epsilon_{\text{min}} = 18.0$ MJ kg$^{-1}$ (i.e., we consider the extreme case where we account for at least some of the undetected cases of females reproducing below $\epsilon_{\text{min}} = 20.0$ MJ kg$^{-1}$, while simultaneously ignoring the possibility of some females not reproducing above $\epsilon_{\text{min}} = 18.0$ MJ kg$^{-1}$).

As expected, reducing the reproduction threshold impacts the predicted proportions of non-reproducing females ($p_0$). For instance, with Early Feeding, we obtain $p_0 = 0.275$, $p_0 = 0.400$ and $p_0 = 0.550$ with $\epsilon_{\text{min}} = 20.0$ MJ kg$^{-1}$ for on-shore arrival dates August 1, July 1 and June 1, respectively, but $p_0 = 0.225$, $p_0 = 0.275$ and $p_0 = 0.400$ for these same dates with $\epsilon_{\text{min}} = 18.0$ MJ kg$^{-1}$. Changes in the Late Feeding scenario are similar, with $p_0$(August 1) = 0.275, $p_0$(July 1) = 0.725 and $p_0$(June 1) = 1.0 when using $\epsilon_{\text{min}} = 20.0$ MJ kg$^{-1}$, but $p_0$(August 1) = 0.225, $p_0$(July 1) = 0.600 and $p_0$(June 1) = 0.950 when using $\epsilon_{\text{min}} = 18.0$ MJ kg$^{-1}$. Females now able to reproduce (i.e., females with energy density between 18.0 MJ kg$^{-1}$ and 20.0 MJ kg$^{-1}$ on October 1) would mostly produce singletons, but a small increase in the proportions of females with twins ($p_2$) would also be observed (Supplementary Fig. S1a,b). The proportion of females producing triplets ($p_3$) is practically independent of the choice for $\epsilon_{\text{min}}$ and remains unaffected by these sensitivity analyses (Supplementary Fig. S1a,b). These changes in $p_0$, $p_1$ and $p_2$ increase expected mean litter size ($X$) for all on-shore arrival dates and both feeding scenarios (Supplementary Fig. S1c,d). For instance, with Early Feeding, we obtain $X$(August 1) = 1.35, $X$(July 1) = 1.05 and $X$(June 1) = 0.75 when using $\epsilon_{\text{min}} = 20.0$ MJ kg$^{-1}$, but $X$(August 1) = 1.42, $X$(July 1) = 1.22 and $X$(June 1) = 0.96 with $\epsilon_{\text{min}} = 18.0$ MJ kg$^{-1}$. With Late Feeding, we obtain $X$(August 1) = 1.35, $X$(July 1) = 0.45 and $X$(June 1) = 0 when using $\epsilon_{\text{min}} = 20.0$ MJ kg$^{-1}$, but $X$(August 1) = 1.42, $X$(July 1) = 0.63 and $X$(June 1) = 0.07 with $\epsilon_{\text{min}} = 18.0$ MJ kg$^{-1}$.

To fully understand the effect of reducing $\epsilon_{\text{min}}$, it is important to note that a change in $\epsilon_{\text{min}}$ affects litter size predictions for all on-shore arrival dates, that is, including the estimated
litter size for females ashore on August 1 which were used to initialize future projections (e.g., $X$(August 1) = 1.35 with $ε_{\text{min}} = 20.0 \text{ MJ kg}^{-1}$, $X$(August 1) = 1.42 with $ε_{\text{min}} = 18.0 \text{ MJ kg}^{-1}$, and $X$(August 1) = 1.57 if $ε_{\text{min}}$ is further reduced to 16.0 MJ kg$^{-1}$). Consequently, at least part of the effects of decreasing $ε_{\text{min}}$ discussed above can be attributed to uncertainty in initial conditions, resulting from a lack of data on non-reproducing females. To control for this uncertainty and thus isolate the impacts of $ε_{\text{min}}$ on litter size predictions, we also calculated expected future changes in mean litter size relative to the mean litter size estimated for females ashore on August 1. For illustration, we show these sensitivity analyses for a wider range of threshold values ($ε_{\text{min}}$ ranging from 14.0 to 22.0 MJ kg$^{-1}$), although we emphasize that we do not consider values at the lower end of this scale realistic estimates of a population averaged reproduction threshold. Threshold values of 12.0 MJ kg$^{-1}$ and lower were not considered here because such den entry energy densities would lead to death by starvation within 4.9 months or less (i.e., before den emergence) even without reproduction (as calculated for the average straight-line body length in our sample of females, $L = 1.95$ m). Supplementary Fig. 2 show these sensitivity analyses, demonstrating that (a) mean litter size is expected to decline substantially with earlier on-shore arrival irrespective of the choice for $ε_{\text{min}}$, and (b) that the expected declines are generally somewhat slower if lower values of $ε_{\text{min}}$ are considered.

In conclusion, new data on non-reproducing females is needed to relax our assumption of an absolute reproduction threshold that is valid for all females of the population. Such data could be used to also estimate $p_0$ by regression and thus better characterize polar bear reproduction at the lower end of the energy density scale. In the absence of such data, we suspect that our original parameterization using $ε_{\text{min}} = 20.0 \text{ MJ kg}^{-1}$ provides conservative predictions of future litter size. However, it is also possible (but thought unlikely) that a threshold lower than $ε_{\text{min}} = 20.0 \text{ MJ kg}^{-1}$ would provide a better approximation of polar bear reproduction. In this case, the numerical predictions for present and future litter size would change somewhat, but all trends and general conclusions would be maintained: the proportion of non-reproducing females would increase monotonically with earlier on-shore arrival, the proportions of females with twins and triplets would decrease monotonically at the same time, and the proportion of females with singletons would remain relatively unaffected in all but the most extreme cases (Late Feeding with
early-June on-shore arrival) (Supplementary Fig. S1a,b). These changes are expected for both feeding scenarios, but they are more pronounced with Late Feeding. In sum, as with $\varepsilon_{\text{min}} = 20.0 \text{ MJ kg}^{-1}$, substantial declines in mean litter size are expected with earlier on-shore arrival, whereas little to no change will be seen in the commonly measured metric $X^*$ (mean litter size conditional on producing at least one cub) (Supplementary Figs. S1c,d and S2).
Supplementary Figure S1 | Sensitivity of litter size predictions to choice of reproduction threshold $\epsilon_{\text{min}}$. Full analyses for expected changes in litter size as a function of on-shore arrival date when using $\epsilon_{\text{min}} = 18.0$ MJ kg$^{-1}$ (red lines). The original predictions for changes in litter size using $\epsilon_{\text{min}} = 20.0$ MJ kg$^{-1}$ (as shown in Fig. 3 of the main text) are included for comparison (black lines). (a), (b) Expected proportions of females producing zero ($p_0$, dot-dashed lines), one ($p_1$, dashed lines), two ($p_2$, solid lines), and three ($p_3$, dotted lines) cubs as a function of on-shore arrival date under the Early and Late Feeding scenarios, respectively. (c), (d) Expected mean litter size ($X$, dashed lines) and expected mean litter size conditional on producing at least one cub ($X^*$, solid lines) as a function of on-shore arrival date under Early and Late Feeding, respectively. Dotted lines show 95% confidence intervals for the predictions with $\epsilon_{\text{min}} = 18.0$ MJ kg$^{-1}$. 
Supplementary Figure S2 | Sensitivity of litter size predictions to choice of $\varepsilon_{\text{min}}$, when controlling for the dependency of the August 1 initial condition on $\varepsilon_{\text{min}}$. Expected mean litter size, $X$, relative to the mean litter size estimate for ashore date August 1, $X$(August 1), as a function of on-shore arrival date. Analyses are shown using reproduction thresholds of 14.0 MJ kg$^{-1}$ (green lines), 16.0 MJ kg$^{-1}$ (blue lines), 18.0 MJ kg$^{-1}$ (red lines), 20.0 MJ kg$^{-1}$ (black lines) and 22.0 MJ kg$^{-1}$ (purple lines) under the (a) Early and (b) Late Feeding scenarios, respectively (see text for details).
Supplementary References

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