



Temperature Effects on BLDC Motor Efficiency and Power Output

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Abstract

Temperature changes the electrical resistance of motor windings and the strength of permanent magnets, but its effect on performance depends on the mechanical load and the drive control. This paper combines a targeted review of published studies with a steady-state model using catalogue parameters for a maxon EC 45 flat 30 W brushless DC motor. The main calculation assumes equal winding and magnet temperatures from 20 °C to 80 °C and fixed torques from 25% to 100% of nominal torque. At a constant 24 V, predicted efficiency falls by 0.4 percentage points at 25% load and 6.4 points at full nominal torque. Output power rises by 5.4% at light load as speed increases, but falls by 2.2% at full load. With speed held constant, output power remains fixed and heating increases input power. The high-load efficiency penalty persists in the sensitivity cases, whereas the light-load change can reverse sign. Catalogue checks reveal substantial discrepancies at the nominal operating point, limiting confidence in absolute predictions. The results support testing improved heat conduction at sustained high loads, but do not establish universal cooling thresholds or a verified safe operating limit.

1 Introduction

Brushless DC (BLDC) motors are used in electric vehicles, drones, robots, pumps and fans. Their efficiency varies with the operating point and with temperature. Understanding that variation matters when a motor must deliver a sustained torque without drawing excessive electrical power or exceeding its thermal limits.

Two material changes are relevant. Copper winding resistance rises with winding temperature, increasing the heat dissipated at a given current. If the rotor uses neodymium magnets, a rise in magnet temperature reduces magnetic flux and the torque constant. The motor then requires more current to produce the same torque. These effects reinforce copper loss, particularly at high load.

Published work reports poorer performance at higher temperatures and better performance with liquid cooling (Kristyadi, Marsono and Sayuti, 2022; Sulistyono and Arta, 2026). However, those studies use different motors, cooling conditions and operating points. Their results cannot be treated as measurements of the temperature effect at a fixed load on the motor considered here.

The research question is: How does motor operating temperature affect the efficiency and power output of a brushless DC motor under different mechanical loads?

We address this question through secondary research and a simplified electrical model. The model separates imposed temperature from load so that their interaction can be examined. It is an illustrative calculation for one reference motor, rather than an experimentally established performance map. Later sections consider self-heating, mounting options and cost under stated assumptions.

2 Background and Theory

2.1 Energy conversion and the equivalent motor model

A BLDC motor has permanent magnets on its rotor and windings on its stator. Electronic commutation switches the phase currents according to rotor position. A simple equivalent DC model relates electromagnetic torque, current, back electromotive force and angular speed:

$$\tau_{em} = kI \quad E = k\omega$$

Here τ_{em} is electromagnetic torque, I is the equivalent motor current, E is back electromotive force and ω is angular speed. The torque constant and back electromotive force constant have equal numerical values when expressed in compatible SI units. This convention must be applied consistently; line, phase and controller supply currents are not interchangeable.

At steady state, the equivalent model is:

$$V = IR + k\omega \quad \tau_L = k(I - I_0)$$

V is the equivalent applied voltage, R is terminal resistance, τ_L is shaft load torque and I_0 represents the current associated with rotational losses. This treatment assumes a constant loss torque at each chosen temperature. It does not resolve the individual phase waveforms or switching losses.

The linear model is a useful approximation, but it does not describe every BLDC motor exactly. maxon identifies EC flat motors as having iron-cored windings and a nonlinear speed versus torque characteristic. Its catalogue data also refer to block commutation; other commutation methods require consistent parameter conventions (maxon, 2024). These restrictions are relevant to the reference motor used here.

2.2 Motor losses and the efficiency boundary

The motor converts input power into shaft output, copper loss, iron loss and mechanical loss. Copper loss is I^2R . Iron losses arise as the magnetic field varies in the stator steel, while mechanical losses include bearing friction and windage. Their relative importance depends on motor construction, current and speed.

The present model combines iron and mechanical losses through I_0 . Its power balance follows directly from the equations in Section 2.1:

$$VI - \tau_L\omega = I^2R + k\omega I_0$$

The residual term $k\omega I_0$ represents rotational loss. It avoids counting I_0 as an additional electrical power loss on top of VI . Controller losses lie outside the model boundary, so the reported efficiency is an equivalent motor efficiency rather than battery-to-shaft efficiency.

2.3 Winding resistance and temperature

For copper, resistance is approximately linear with temperature over the range considered:

$$R(T_w) = R_{20}[1 + \alpha_{Cu}(T_w - 20)]$$

T_w is average winding temperature in °C, R_{20} is resistance at 20 °C and α_{Cu} is 0.00393 °C⁻¹ at that reference temperature (National Bureau of Standards, 1966). Heating from 20 °C to 80 °C therefore increases resistance by 23.6%.

Resistance can also be used to estimate average winding temperature from a known cold resistance. Such a measurement requires correction for lead and contact resistance and does not reveal local hot spots. Increasing R alone does not increase the current required for a fixed torque in this model; it increases copper loss and the voltage needed to sustain speed.

2.4 Magnet temperature and the motor constant

The remanence of neodymium iron boron magnets decreases as temperature rises. Supplier guidance gives reversible coefficients of approximately -0.08% to -0.12% per $^{\circ}\text{C}$, depending on grade (e-Magnets UK, n.d.). Assuming the torque constant follows magnet flux gives:

$$k(T_m) = k_{20}[1 + \alpha_{Br}(T_m - 20)]$$

T_m is magnet temperature and α_{Br} is the assumed reversible coefficient. At -0.12% per $^{\circ}\text{C}$, a rise from 20°C to 80°C reduces k by 7.2% . Winding temperature and magnet temperature are distinct physical quantities; setting them equal is an explicit simplification of the main calculation.

maxon identifies the EC flat family as using neodymium rotor magnets (maxon, 2014), but the exact grade of the reference motor is not published in the cited product data. The familiar 80°C guidance for some standard neodymium grades is not a universal demagnetisation threshold. The magnetic circuit, opposing field and grade affect the working limit (e-Magnets UK, n.d.). A 125°C winding rating does not establish the rotor magnet rating.

2.5 Heat flow and self-heating

A simple thermal network represents heat flowing from the winding to the housing and from the housing to ambient air. If only copper loss is included, steady winding temperature satisfies:

$$T_w = T_a + (R_{th1} + R_{th2})P_{Cu}$$

T_a is ambient temperature, R_{th1} is winding-to-housing thermal resistance and R_{th2} is housing-to-ambient thermal resistance. This copper-only relation is used in manufacturer engineering guidance (maxon motor, 2009). It is approximate because losses occur in different parts of the motor and the rotor needs a separate thermal path. Installation also changes heat removal.

The reference motor's winding and whole-motor thermal time constants are 10.3 s and 288 s respectively (maxon, n.d.a). A time constant describes the rate of approach to equilibrium, not the time at which equilibrium is complete. During operation the housing can be cooler than the winding, so housing temperature alone is an incomplete measure of thermal margin.

2.6 Why the mechanical load matters

When load current is much greater than I_0 , copper loss can be approximated by:

$$P_{Cu} \approx \frac{\tau_L^2}{k^2(T_m)} R(T_w)$$

For equal winding and magnet temperatures, heating from 20°C to 80°C multiplies this loss by approximately $1.236/0.928^2 = 1.435$ in the base case. The additional heat is therefore about 44% of a quantity that already grows with torque squared. The absolute penalty is much greater at high torque.

Output power also depends on speed. At fixed voltage, weaker magnets tend to increase speed through the smaller back electromotive force constant, while the larger resistive voltage drop tends to reduce it. Either effect can dominate. If a controller instead holds both torque and speed constant, shaft power is fixed and temperature affects the required input power and voltage.

2.7 Published evidence

Sulistyo and Arta (2026) tested a nominal 3 kW BLDC drive over 750 to 2000 rpm. Across that range, housing surface temperature measured with a thermal camera rose from 34.8 °C to 87.3 °C while torque fell from 37.37 N·m to 19.38 N·m. These are associated changes across operating points, rather than an isolated temperature test. The data cannot determine how much of the torque change was caused by heating.

Kristyadi, Marsono and Sayuti (2022) investigated cooling of a nominal 20 kW axial-flux BLDC motor using numerical modelling and experiments. They report experimental output of 25 kW at 81.0% efficiency with water cooling, compared with 19.1 kW at 65.0% with air cooling. Their numerical results at 6000 rpm give efficiencies of 78.1% and 58.3% for air temperatures of 27 °C and 50 °C. Those particular efficiency values are simulated, not measured.

Together, the studies show that thermal conditions are relevant to BLDC performance. Neither provides a directly comparable temperature and load map for the small reference motor. They give context for the model, but cannot validate its predicted numerical changes.

3 Research Methodology

3.1 Research design and source selection

This study combines a targeted narrative review, manufacturer data and deterministic calculations. It uses two published studies for thermal performance context, maxon product and technical documentation for motor parameters, and materials data for temperature coefficients. It is not a systematic review and does not claim exhaustive coverage of the literature.

Sources are used according to their purpose. Manufacturer data define the catalogue operating points and thermal parameters. Materials references support the copper and magnet coefficients. Published experiments and simulations are distinguished when their findings are discussed. Comparisons retain the original temperature definition, such as ambient air or a reported motor temperature, rather than treating every temperature as a winding measurement.

3.2 Data extraction and processing

The electrical inputs are nominal voltage, terminal resistance, torque constant, no-load current and nominal torque. Thermal inputs are the two thermal resistances and maximum winding temperature. Torques are converted from mN·m to N·m before calculation, and angular speed is converted to rpm using $n = 30\omega/\pi$.

The cited literature values are taken from reported numerical results. No new experimental measurements or graph digitisation are claimed. Efficiency differences are reported in percentage points. Relative output-power changes are calculated against the 20 °C result at the same torque. Values are rounded only after calculation, so differences calculated from displayed table entries may vary slightly.

3.3 Reference motor and assumptions

The reference is the 24 V maxon EC 45 flat 30 W motor with Hall sensors, part 339281. It is retained as a documented case because its public data provide the required inputs. The catalogue power designation is not imposed as a constant shaft output. Load is defined as a fraction of its nominal torque, 56.9 mN·m.

Resistance and torque constant are referenced to 25 °C in the manufacturer documentation. They are converted to a consistent 20 °C baseline:

$$R_{20} = \frac{R_{25}}{1 + 5\alpha_{Cu}} \quad k_{20} = \frac{k_{25}}{1 + 5\alpha_{Br}}$$

The main calculation sets $T_w = T_m = T$, holds I_0 at 0.0818 A and uses $\alpha_{Br} = -0.0012 \text{ } ^\circ\text{C}^{-1}$. Temperature is externally specified, independently of torque. Thus, the main grid is a comparison of imposed material temperatures, not a prediction that every operating point reaches those temperatures naturally.

3.4 Electrical calculations and sensitivity cases

For each temperature and shaft torque, the following quantities are calculated in order:

$$I = \frac{\tau_L}{k(T_m)} + I_0 \quad \omega = \frac{V - IR(T_w)}{k(T_m)}$$

$$P_{out} = \tau_L \omega \quad P_{in} = VI \quad \eta = \frac{P_{out}}{P_{in}}$$

The grid contains 28 cases: $T = 20, 30, 40, 50, 60, 70$ and $80 \text{ } ^\circ\text{C}$, at 25%, 50%, 75% and 100% of nominal torque. Supply voltage is 24 V. The $80 \text{ } ^\circ\text{C}$ endpoint defines the comparison range; it is not a verified limit for this motor.

Four additional scenarios test assumptions separately: $\alpha_{Br} = -0.0008 \text{ } ^\circ\text{C}^{-1}$; I_0 reduced in proportion to k/k_{20} ; constant speed at each load's $20 \text{ } ^\circ\text{C}$ base-case speed; and winding heating with the magnets held at $20 \text{ } ^\circ\text{C}$. The I_0 scenario is an exploratory reduction in rotational loss, not an established temperature law or a physical upper bound. In the constant-speed case the required voltage is calculated as $V_{req} = IR + k\omega$. Each sensitivity change is applied on its own.

3.5 Checks against manufacturer data

Using $25 \text{ } ^\circ\text{C}$ motor parameters, the model is compared with catalogue no-load speed, stall torque, maximum efficiency and nominal speed. Nominal speed and torque are defined at $25 \text{ } ^\circ\text{C}$ motor temperature. The listed nominal current has a different basis: continuous operation at $25 \text{ } ^\circ\text{C}$ ambient reaching the permitted winding temperature (maxon, 2019). Its comparison is included as a consistency screen, not a matched-temperature validation test. A 5% relative discrepancy is used as an analyst-selected screening criterion, rather than a statistical confidence interval or manufacturer tolerance. Maximum efficiency is found by maximising the model efficiency over its positive-torque motoring range.

Agreement with catalogue values checks internal consistency and the suitability of the approximation. Some catalogue quantities, including stall torque, are themselves calculated from ideal relationships (maxon, 2019). Reproducing them is therefore not independent experimental validation and does not verify the temperature coefficients. The nominal operating point is particularly important because a good no-load fit alone does not establish accuracy under load.

3.6 Thermal and financial calculations

For the self-heating illustration, the electrical equations are coupled to the thermal relation in Section 2.5. The same $20 \text{ } ^\circ\text{C}$ resistance and magnet references are used throughout. A root of the heat-balance equation is sought between ambient temperature and $125 \text{ } ^\circ\text{C}$. The lowest equilibrium reached from the

cold condition is reported where it exists. A missing root within this interval means only that no equilibrium is found within the permitted winding-temperature range under these assumptions.

The thermal calculation counts copper heating only and sets magnet temperature equal to winding temperature. Neither assumption is sufficient for a validated thermal model. Values above 80 °C extend the material equations beyond the main comparison grid and are reported only as exploratory estimates.

The engineering case holds shaft torque and speed constant so that all options perform the same mechanical duty. Annual energy is input power multiplied by 4000 operating hours, divided by 1000 to obtain kWh. Simple payback is additional capital cost divided by annual energy-cost saving. Labour, installation, maintenance, discounting and controller losses are excluded.

3.7 Reporting and reproducibility

All calculated values are predictions. The equations, inputs, temperature range, load definitions and sensitivity changes are given so that the results can be reproduced. The calculation procedure is summarised in the appendix. Claims from experiments, published simulations and the present model remain separate throughout the paper.

4 Results

4.1 Reference parameters

Table 1 lists the parameters used in the base case. The manufacturer specifies a maximum winding temperature of 125 °C. This rating is used only as the upper boundary of the exploratory heat-balance calculation.

Table 1 Reference parameters for maxon part 339281

Parameter	Catalogue reference	20 °C model baseline
Nominal voltage	24 V	24 V
Terminal resistance	4.55 Ω at 25 °C	4.4623 Ω
Torque constant	50.9 mN·m/A at 25 °C	51.2072 mN·m/A
No-load current	81.8 mA	81.8 mA
Nominal shaft torque	56.9 mN·m	56.9 mN·m
Winding-to-housing resistance	3.92 K/W	3.92 K/W
Housing-to-ambient resistance	6.55 K/W	6.55 K/W

Source: maxon (n.d.a). Only resistance and torque constant are temperature-converted. Nominal torque is used as a fixed load reference.

4.2 Comparison with the catalogue

The model closely reproduces no-load speed, stall torque and maximum efficiency, but overestimates nominal speed by 13.3%, beyond the 5% screening criterion. The separate current consistency check differs by 11.1%, although the temperature definitions are not matched (Table 2).

Table 2 Catalogue consistency checks using 25 °C motor parameters

Quantity	Catalogue	Model	Relative difference
No-load speed	4390 rpm	4433 rpm	+1.0%
Stall shaft torque	268 mN·m	264.3 mN·m	-1.4%
Maximum efficiency	77.0%	76.6%	-0.5%
Nominal speed	3070 rpm	3479 rpm	+13.3%
Nominal current ¹	1.08 A	1.20 A	+11.1%

Sources: maxon (n.d.a; 2019). ¹ Catalogue nominal current uses a continuous thermal limit at 25 °C ambient; the calculation uses 25 °C motor parameters. Its difference is not a matched-temperature error. All differences above are relative percentages, including the efficiency row.

Maximum efficiency differs by about 0.4 percentage points, equivalent to roughly 0.5% of the catalogue efficiency. The nominal-point discrepancies remain material. Matching the catalogue speed gradient through R/k^2 does not resolve them, because the reference motor's true characteristic is nonlinear. The model is therefore suitable for an illustrative parameter study, with limited confidence in its absolute operating-point predictions.

4.3 Efficiency and output power at imposed temperatures

At constant 24 V, predicted efficiency decreases with temperature in every base-case load row. The drop from 20 °C to 80 °C is 0.4 percentage points at 25% load and 6.4 points at full nominal torque (Table 3).

Table 3 Predicted motor efficiency at constant 24 V in percent

Load	20 °C	30 °C	40 °C	50 °C	60 °C	70 °C	80 °C
25%	72.1	72.0	72.0	71.9	71.8	71.7	71.7
50%	76.8	76.4	76.0	75.6	75.2	74.7	74.2
75%	75.6	74.9	74.1	73.4	72.6	71.8	71.0
100%	72.5	71.5	70.5	69.4	68.3	67.2	66.1

Load is a percentage of nominal shaft torque. All temperatures in this table assume $T_w = T_m$. Values are model predictions; controller losses are excluded.

Figure 1 shows that the temperature slope becomes steeper as load increases. The highest efficiency among the four sampled loads occurs at 50% of nominal torque. That is a result of this motor and loss approximation, not a general rule for BLDC motors.

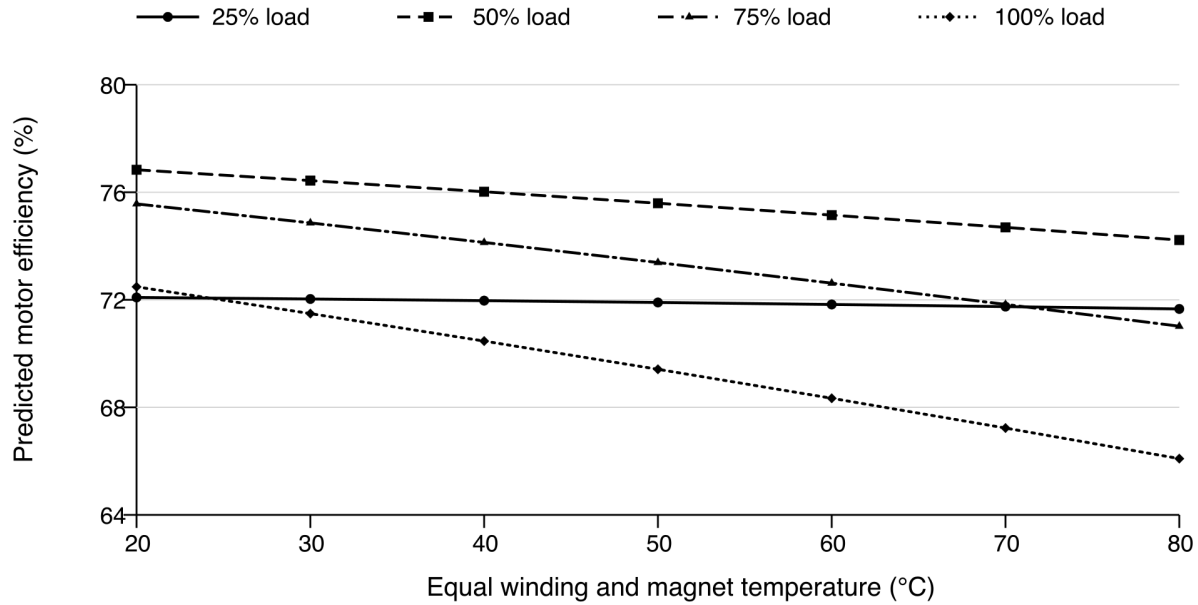


Figure 1 Predicted efficiency for maxon EC 45 flat part 339281 at constant 24 V. Loads are fractions of nominal shaft torque; winding and magnet temperatures are assumed equal.

Output power has a different pattern (Table 4). It increases by 5.4% at 25% load and by 3.1% at 50% load. The change is small at 75% load, while full-load output falls by 2.2%.

Table 4 Predicted shaft output at constant 24 V in watts

Load	20 °C	30 °C	40 °C	50 °C	60 °C	70 °C	80 °C
25%	6.22	6.27	6.33	6.38	6.44	6.50	6.56
50%	11.75	11.82	11.88	11.94	12.00	12.06	12.12
75%	16.60	16.62	16.65	16.67	16.68	16.69	16.70
100%	20.75	20.70	20.64	20.57	20.48	20.39	20.29

Load is a percentage of nominal shaft torque. All temperatures in this table assume $T_w = T_m$. Values are model predictions; controller losses are excluded.

4.4 Changes between the endpoints

Table 5 separates efficiency, shaft power, speed and copper loss. Copper loss rises at every load, even where shaft output rises. Higher output at fixed voltage therefore does not imply better energy conversion.

Table 5 Predicted changes from 20 °C to 80 °C at constant 24 V

Load	Efficiency change	Output change	Speed in rpm	Copper loss in W
25%	−0.4 pp	+5.4%	4176 to 4400	0.58 to 0.80
50%	−2.6 pp	+3.1%	3945 to 4069	1.81 to 2.55
75%	−4.5 pp	+0.6%	3714 to 3737	3.74 to 5.29
100%	−6.4 pp	−2.2%	3483 to 3405	6.35 to 9.02

pp = percentage points. Endpoint changes use unrounded values. Winding and magnet temperatures are assumed equal.

At 20 °C, copper loss accounts for approximately 24% of the model's total loss at 25% load and 81% at full nominal torque. Heating adds about 0.22 W and 2.67 W of copper loss respectively. This difference in additional watts explains why load strongly affects the efficiency penalty.

4.5 Sensitivity to assumptions

The four sensitivity scenarios are compared with the base case in Table 6. The full-load efficiency penalty persists, but the size of the change and the light-load trend depend on the assumptions.

Table 6 Sensitivity of endpoint efficiency and output changes

Scenario	$\Delta\eta$ 25%	$\Delta\eta$ 50%	$\Delta\eta$ 75%	$\Delta\eta$ 100%	ΔP 25%	ΔP 100%
Base case	−0.4	−2.6	−4.5	−6.4	+5.4%	−2.2%
Magnet coefficient −0.08%/°C	−0.7	−2.5	−4.2	−5.9	+2.9%	−3.8%
I_0 proportional to k	+0.8	−1.8	−4.0	−6.0	+5.5%	−2.0%
Speed held constant	−0.8	−3.0	−4.6	−6.0	+0.0%	+0.0%
Magnets held at 20 °C	−1.2	−2.4	−3.7	−4.9	−1.7%	−6.7%

Efficiency changes are in percentage points for 20 °C to 80 °C. Power changes are relative percentages. Each scenario changes one assumption; the magnet-coefficient case recalculates its 20 °C reference from the same 25 °C catalogue value.

Reducing I_0 with k changes the sign of the light-load efficiency result. The main calculation therefore cannot establish whether heating slightly improves or reduces efficiency at low torque without a better rotational-loss model. Holding the magnets cold also removes the speed increase caused by reversible magnet weakening.

With speed held constant, shaft power is unchanged by definition. At full nominal torque and 80 °C, maintaining the 20 °C speed requires approximately 24.4 V at the equivalent motor terminals. Controller voltage drops would require additional supply margin.

4.6 Exploratory self-heating

Table 7 gives copper-only heat-balance estimates at 25 °C ambient. These are conditional on equal winding and magnet temperatures and the catalogue thermal resistances.

Table 7 Exploratory free-air equilibrium at 25 °C ambient

Load	Predicted winding temperature
25%	31.4 °C
50%	47.3 °C
75%	80.6 °C
100%	No equilibrium found at or below 125 °C

Copper heating only, catalogue thermal resistances and $T_m = T_w$. The 75% result slightly exceeds the 80 °C comparison range. These are exploratory predictions, not operating limits.

At full nominal torque the equal-temperature calculation finds no equilibrium below the 125 °C winding rating. In an additional idealised thermal sensitivity case with the rotor held at the 25 °C ambient temperature, a stable full-load winding equilibrium appears at 118.2 °C. Holding the rotor at ambient is not a prediction of passive cooling, but the difference shows how strongly the result depends on rotor temperature. Neither case proves thermal runaway in the real motor. The loaded-point mismatch, omitted losses and installation dependence require a more complete thermal assessment.

5 Analysis and Discussion

5.1 The load dependence of efficiency

The results support the expected increase in temperature sensitivity at high torque. Resistance rises by the same fraction at every imposed winding temperature, and the assumed magnet coefficient is also independent of load. What changes is the current and the amount of copper loss to which those temperature factors apply.

In the base case, copper loss rises by about 39% at 25% load and 42% at full nominal torque between 20 °C and 80 °C. These factors are slightly below the approximate 44% result in Section 2.6 because the fixed I_0 term does not increase with $1/k$. At high torque, the extra copper loss forms a substantial share of input power. At light load, the rotational-loss approximation has greater influence on efficiency.

5.2 Power output and control mode

At fixed voltage and torque, shaft power changes only because speed changes. In the equal-temperature base case, the smaller k raises speed at light load more than the larger resistive drop lowers it. The two effects balance at roughly 81% of nominal torque over the 20 °C to 80 °C interval. This crossover changes with the magnet coefficient and loss assumptions.

The light-load power increase should not be interpreted as a benefit of overheating. Current and losses also rise, while the speed may no longer suit the application. Under constant-speed control, the useful shaft output is fixed and additional electrical input supplies the extra losses. A controller can maintain that condition only while its current and voltage limits allow it.

5.3 What the sensitivity analysis establishes

The high-load penalty is consistent across the scenarios tested. This supports the underlying copper-loss mechanism, but it does not assign a confidence interval to the numerical result. The cases vary one assumption at a time and do not cover all parameter tolerances, nonlinear losses or combinations of uncertainty.

The fixed-magnet-temperature case is especially relevant because the winding and rotor can operate at different temperatures. The main result combines winding heating with magnet heating. It cannot be interpreted as the effect of winding temperature alone. Separate temperature measurements would be needed to determine which scenario best represents a real installation.

5.4 Relationship to published work

The cited studies are compatible with the broader finding that thermal conditions affect performance, but the numerical changes cannot be compared directly. Sulistyo and Arta (2026) change speed as temperature changes; their torque reduction cannot be assigned wholly to temperature, or divided reliably between speed and heating from the reported comparison.

Kristyadi, Marsono and Sayuti (2022) examine a much larger axial-flux motor and different cooling conditions. Their 19.8 percentage point numerical efficiency change refers to a 23 °C rise in surrounding air temperature, not a 23 °C rise imposed on both windings and magnets. Motor size, speed, cooling and loss models all differ. These differences prevent the literature from verifying the magnitude of the present predictions.

The simplified model is not a guaranteed lower bound on real losses. Omitted losses may increase heat generation, while assumed rotor heating or the constant I_0 treatment may exaggerate other effects. The net error requires measurement.

5.5 Thermal feedback

The electrical and thermal calculations describe related but different questions. The imposed-temperature grid shows how material changes affect an operating point. The heat-balance calculation asks which temperature might follow from a given load and cooling path. Combining them introduces feedback: higher losses raise temperature, and higher temperature can raise losses further.

The predicted 75% load equilibrium lies near 80 °C in free air, making the result sensitive to the assumed thermal path. It supports investigating improved mounting at that duty. It does not establish that every motor above 75% nominal torque needs additional cooling or that every motor below 50% is thermally safe.

6 Evaluation and Limitations

The main strength of the study is that it makes load, temperature and control mode explicit. Inputs are traceable, the electrical calculations can be reproduced, and the sensitivity cases show where the result depends on uncertain assumptions. The separation of shaft power from efficiency also explains why temperature can increase one while reducing the other.

The largest limitation is the incomplete agreement with the reference motor's nominal operating point. The linear equivalent model does not reproduce the nonlinear behaviour of an iron-cored EC flat motor. Its close no-load and peak-efficiency checks are useful consistency checks, but do not overcome that loaded-point error.

A second limitation is temperature representation. The main grid imposes equal winding and magnet temperatures, while a real motor has separate thermal paths and local hot spots. The magnet coefficient is assumed rather than measured for the exact grade. The model also keeps I_0 independent of speed in its base case, despite the speed dependence of rotational losses in brushless motors.

The thermal illustration includes copper heating only and uses fixed thermal resistances. It omits heat from iron and mechanical losses, changes in convection with speed, and the detailed motor-to-mount contact. Predicted temperatures may therefore be either too high or too low. The 25% and 50% reductions in housing-to-ambient resistance are scenarios, not tested properties of a specified plate.

Finally, one small motor and two contextual research papers cannot establish performance changes for the full BLDC motor class. Sulistyo and Arta's paper also gives inconsistent shaft-power values between its tables, which limits its usefulness as a quantitative benchmark. No statistical uncertainty is assigned because the present study contains no repeated measurements or calibrated probability model. The financial estimate is similarly conditional on operating hours, tariffs, installation cost and the predicted input powers.

7 Engineering Recommendation

7.1 Application-specific thermal assessment

For sustained high torque, assess the winding temperature, mounting and drive limits before choosing a cooling measure. The present results support paying particular attention to copper loss as load increases. They do not justify a fixed percentage-of-nominal-torque rule for all motors.

For the reference motor, a conductive metal mounting is a reasonable first option to test. It can improve heat transfer without changing the motor, but its effect depends on contact area, interface material, plate geometry and airflow. Winding temperature can be estimated from resistance or measured with an appropriate sensor; magnet temperature and its permitted operating range need separate consideration.

Both motors used in the comparison are listed by the manufacturer as not recommended for new designs (maxon, n.d.a; maxon, n.d.b). They remain useful research examples. A new product should be assessed using a currently recommended motor and its applicable installation guidance.

7.2 Case study at a fixed mechanical duty

The example application requires 42.675 mN·m at approximately 3714 rpm, giving 16.60 W of shaft output. This is 75% of the reference motor's nominal torque. A constant-speed drive is assumed so that cooling options are compared at equal useful output.

Option A uses the reference motor with its catalogue free-air thermal resistances. Option B reduces R_{th2} by an assumed 25% or 50% through conductive mounting. These are plausible scenarios in view of manufacturer mounting guidance, rather than verified plate performance (maxon motor, 2009). Option C uses a maxon EC 45 flat 50 W motor, part 339286, at the same torque and speed. Its catalogue values are $R_{25} = 2.83 \Omega$, $k_{25} = 47.5 \text{ mN}\cdot\text{m/A}$, $I_0 = 0.106 \text{ A}$, $R_{th1} = 4.43 \text{ K/W}$ and $R_{th2} = 5.44 \text{ K/W}$ (maxon, n.d.b). The duty is approximately 61% of its nominal torque.

Table 8 Predicted options at equal torque and speed

Option	Winding at 25 °C ambient	Winding at 40 °C ambient	Efficiency at 25 °C ambient	Input at 25 °C ambient
A Free air 30 W	80.6 °C	102.8 °C	70.9%	23.42 W
B Mounting R_{th2} –50%	58.8 °C	77.6 °C	72.6%	22.85 W
B Mounting R_{th2} –25%	69.0 °C	89.2 °C	71.8%	23.11 W
C Free air 50 W	59.4 °C	78.3 °C	75.6%	21.96 W

All options deliver 16.60 W. Mounting reductions are assumptions. Temperatures use copper-only heat balance with $T_m = T_w$; results above 80 °C extrapolate the material relationships beyond the main grid.

The 50% mounting scenario and the larger motor produce similar winding-temperature estimates at 25 °C ambient. The larger motor has the better predicted efficiency, partly because its resistance is lower. The same temperature reduction cannot be assumed from an arbitrary mounting plate, and winding temperatures below 80 °C do not certify protection against magnet demagnetisation.

Option B is the preferred candidate for a mounting test if the existing motor must be retained. Option C remains relevant where installation constraints, continuous-duty requirements or verified performance favour a different motor. Selection should follow measured temperatures and drive checks rather than the model alone.

8 Financial Evaluation

8.1 Cost assumptions

The example assumes 4000 operating hours per year and electricity at €0.1837/kWh. The tariff is Eurostat's EU average for medium non-household consumers in the second half of 2025, including non-recoverable taxes and excluding VAT and other recoverable taxes (Eurostat, 2026). It is an illustrative tariff rather than a quoted price for a small motor installation.

The product pages list €99.47 for part 339281 and €146.00 for part 339286 at quantities of one to four, excluding VAT. The larger motor therefore adds €46.53 before installation. Prices are snapshots accessed on 21 October 2026.

A €3 material allowance is used for conductive mounting. For context, RS Components lists a $500 \times 300 \times 2$ mm aluminium sheet at £37.42 excluding VAT. Dividing its area into fifteen 100×100 mm blanks gives £2.49 per blank before cutting allowance, waste, drilling and labour (RS Components, n.d.). The €3 figure is a budget assumption, not a fabricated-part quotation or evidence of a particular thermal improvement.

8.2 Annual cost and simple payback

Table 9 applies the predicted steady input powers in Table 8 at 25 °C ambient. Costs are calculated from unrounded powers. Payback includes the stated additional material or motor cost only.

Table 9 Estimated annual energy cost at 25 °C ambient

Option	Extra cost	Energy kWh	Annual cost	Annual saving	Payback years
A Free air	€0.00	93.7	€17.21	€0.00	Baseline
B R_{th2} –50%	€3.00	91.4	€16.79	€0.42	7.2
B R_{th2} –25%	€3.00	92.4	€16.98	€0.23	13.1
C Larger motor	€46.53	87.9	€16.14	€1.07	43.5

Assumptions: 4000 h/year and €0.1837/kWh. Additional costs exclude fabrication, installation, VAT and controller changes. Savings and payback use unrounded input powers.

The full 50% mounting scenario saves less than €0.50 per year under these assumptions. Even this favourable material-only estimate takes several years to repay the €3 allowance. Cutting, installation or a shorter service life would lengthen the payback. The larger motor saves more electricity, but its additional purchase cost takes several decades to recover from energy savings alone.

8.3 Interpretation

These estimates favour testing an existing conductive mounting or a low-cost mounting change before buying a larger motor solely to reduce electricity use. They do not show that cooling has no economic value. Reduced temperature may improve operating margin, but this study contains no failure-rate or service-life data with which to price that benefit.

The plate allowance also assumes shared sheet material. Buying a whole sheet for a single motor would give a substantially different cost. Energy savings scale with operating time and the tariff, while

installation costs do not necessarily scale in the same way. The efficiencies of a 30 W motor should not be transferred directly to a kilowatt-scale drive for a financial forecast.

9 Conclusion

The effect of temperature on BLDC performance depends on load and control mode. In the equal winding and magnet temperature model, heating from 20 °C to 80 °C at constant 24 V reduces efficiency by 0.4 percentage points at 25% nominal torque and by 6.4 points at full nominal torque. The greater high-load penalty follows from the increase in copper loss at higher current.

Output power does not always fall as temperature rises. At fixed voltage and torque, the model predicts a 5.4% increase at light load as speed rises, and a 2.2% decrease at full load as the resistive drop becomes more important. At fixed speed and torque, shaft power remains constant and heating increases electrical input. Light-load efficiency is particularly sensitive to the treatment of rotational losses.

These are conditional model results, supported by material relationships and contextual literature rather than new experiments. The nominal-point discrepancies and the assumption of equal winding and magnet temperatures limit their numerical accuracy. Conductive mounting is a practical option to test for the sustained-load example, but its temperature reduction, operating safety and economic value require verification for the actual installation.

10 Further Research

The priority is a controlled bench test on a motor with fully specified commutation and current conventions. Measure torque, speed, motor-terminal electrical power and controller input power separately. Determine winding temperature from resistance or an embedded sensor, and obtain an independent rotor-temperature estimate where practical. Repeat the temperature and load conditions to quantify measurement uncertainty.

The next model should separate winding, housing and rotor temperatures and include speed-dependent iron and mechanical losses. Testing multiple mounting arrangements would establish how contact and plate geometry change R_{th2} . Repeating the work on a second motor would show whether the load dependence transfers beyond the selected EC flat example.

A transient thermal model would then allow short overloads and realistic duty cycles to be assessed. Financial work should use measured power savings, local tariffs, fabrication and installation quotations, and service-life evidence before assigning a monetary benefit to lower temperature.

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Appendix Calculation procedure

The following sequence reproduces the main results. Use SI units and retain full precision until the reporting stage.

1. Convert the catalogue resistance and torque constant from 25 °C to their 20 °C references using the equations in Section 3.3.
2. For each temperature and torque fraction, calculate $R(T_w)$ and $k(T_m)$, then I , ω , P_{out} , P_{in} and η using Sections 2 and 3. Exclude non-motoring points with non-positive speed or input power.
3. Calculate endpoint differences at the same load. Multiply the efficiency difference by 100 for percentage points; calculate relative power change as $100[P_{out}(80)/P_{out}(20) - 1]$.
4. Recalculate the full grid for each separate sensitivity scenario. For constant speed, retain each load's 20 °C base-case ω and calculate the required voltage before calculating input power.
5. For thermal cases, solve $F(T) = T_a + (R_{th1} + R_{th2})I(T)^2R(T) - T = 0$ within the stated temperature interval. Confirm that the cold-start equilibrium is stable and report when no equilibrium lies below 125 °C. Use the same reference conversion in the thermal and electrical calculations.
6. At the fixed shaft duty in Section 7, evaluate the required voltage and input power at each predicted temperature. Calculate annual energy, cost, savings and simple payback from the assumptions in Section 8.