PVC insulated electrical cables pose a fire risk

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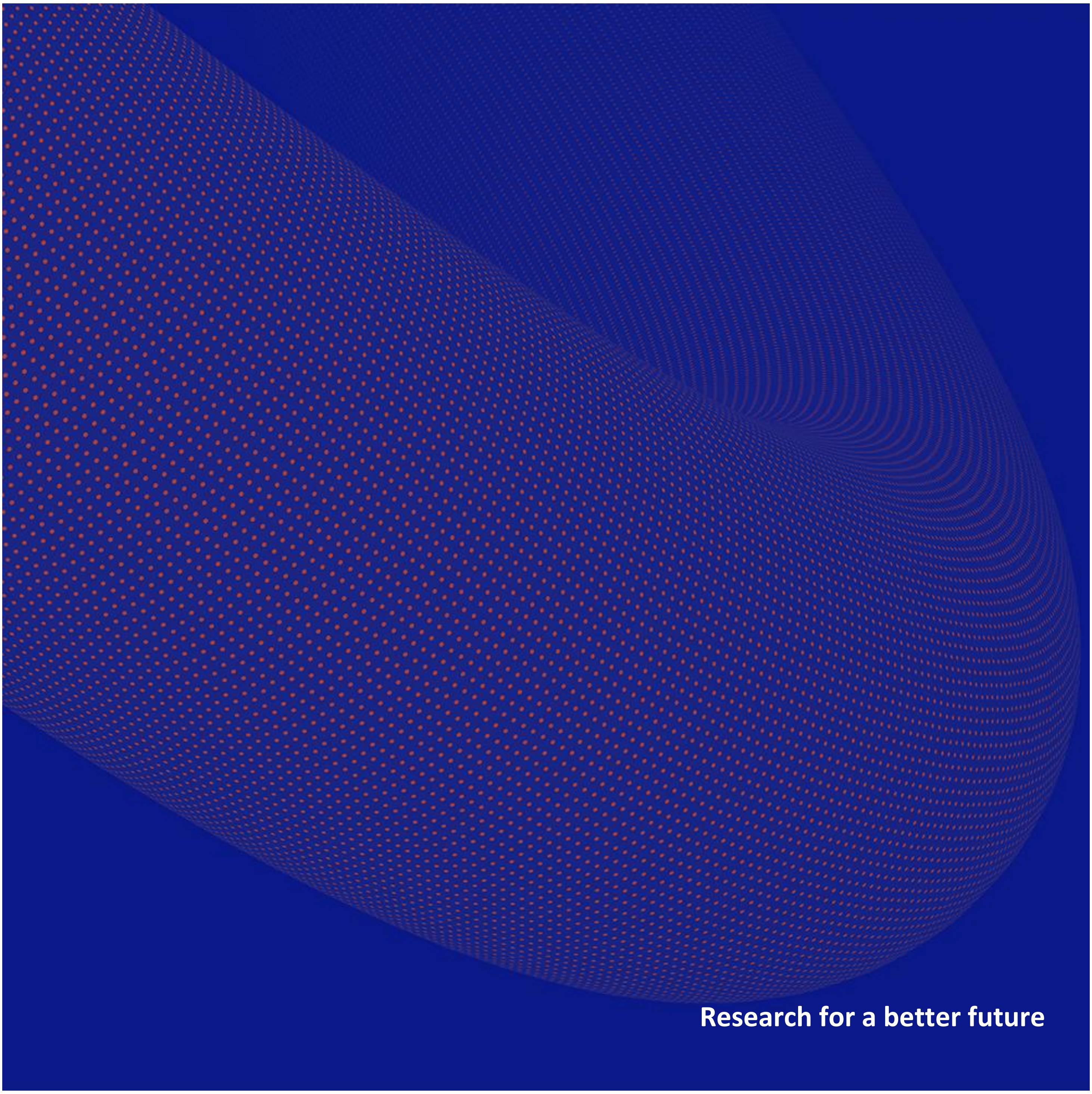

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Summary:

Norwegian and international fire statistics show that building fires with electrical causes have a higher cost than fires with other causes, both in terms of loss of human life and material assets. This suggests that measures that can reduce the incidence of fires with electrical causes have a particularly high value to the society. In the Norwegian fire statistics, the causal category "series arc" is large, with a share of around 35 % of all dwelling fires with electrical causes. This indicates that series faults (contact failure) occur frequently in low voltage electrical installations in Norway.

PVC plastic is used extensively in low voltage electrical installations, primarily as a cable insulation material. PVC insulated electrical cables have an E_{ca} classification in the Construction Products Regulation, and NEK 400 permits the use of cables with an E_{ca} classification in a number of applications, including residential buildings. The thermal decomposition of PVC is problematic and causes the insulation properties of PVC to deteriorate at elevated temperatures. This means that PVC has unsatisfactory properties in terms of resisting the formation of carbonized paths and creep currents. The decomposition also leads to the outgassing of many different combustible gases. Several research studies indicate that PVC has a very adverse effect on the course of a series fault due to the elevated temperatures that occur in such a fault situation. This connection has been strengthened by the review of several specific fire investigation cases where PVC insulation appears to be a contributing factor to a series fault developing into the ignition of a fire. There are strong indications that a thermally stable cable insulation material that maintains its insulation properties at elevated temperatures could reduce the risk of a series fault in a low voltage electrical system developing into a fire.

Based on the findings in this literature review, it appears problematic from an electrical safety perspective that PVC is still permitted to be used as insulation material in low voltage electrical installations. Most of the reviewed evidence points to phasing out PVC as a logical measure. There are already alternative insulation materials in the market that are thermally stable and economically competitive compared to PVC. An example of such an insulating material is cross-linked polyethylene. It is recommended that a review of the requirements imposed on electrical cables and their applications be made at the next revision of NEK 400. The reaction of an electrical cable to fire should not be the only criterion for determining its application. The electrical safety aspect must be emphasized, especially when it can be demonstrated that the use of PVC insulation material brings along an increased risk of fire in low voltage electrical installations.

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Contents

1 Introduction

Norwegian and international fire statistics show that series faults occur frequently in low-voltage electrical installations, and every year this type of fault leads to countless building fires with extensive consequences to the society. It is therefore of great interest to establish measures that protect against series faults in low voltage electrical systems. A series fault is a form of contact failure that can result in resistance heating in a live electrical circuit. Such a local increase in temperature may adversely affect surrounding insulation materials, especially the polymer material polyvinyl chloride (PVC), which exhibits inadequate thermal stability. This material is known to decompose and char, which means that its insulation properties can be weakened already at temperatures exceeding 60-70°C. There are currently alternative polymer materials that have good insulation properties and are thermally stable, including cross-linked polyethylene (PEX). The main hypothesis for this study is that the use of PEX as a cable insulation material in low-voltage electrical installations will be an effective fire prevention measure. By using PEX insulated electrical cables, one can reduce the risk of a series fault causing ignition of a fire.

The purpose of this work is to provide an independent assessment of the impact of cable insulation materials on fire risk in buildings, mainly based on published scientific literature and information obtained from authorities, subject matter experts, and cable manufacturers. The work is limited to a literature review, which means that no new research has been conducted in this project. Furthermore, the project is limited to investigating the two most widespread cable insulation materials, namely PVC and PEX.

The report will shed light on key issues related to the use of PVC insulated electrical cables in low voltage electrical installations. This may, for example, be whether there are insulation materials in today's market that can be an adequate substitute for PVC plastic, and whether the current requirements for electrical cables are sensible, seen from an electrical safety perspective. The report will initially present relevant statistics for fires with electrical causes, then provide an overall technical description of the phenomenon of series faults in low voltage electrical systems, followed by a review of important properties and performance requirements for cable insulation materials. Finally, some considerations related to the challenges and possible risks associated with the use of PVC insulated electrical cables are presented.

2 Fire statistics

In many Western countries there are detailed fire statistics, but only some of these have been made publicly available. In addition, the level of detail and categories often varies from country to country, making accurate comparisons a challenge. In this chapter, the focus is limited to statistics for building fires with electrical causes, as these are most relevant for assessments related to the choice of insulation materials in low voltage installations.

The Norwegian Directorate for Civil Protection (DSB) has compiled statistics for fires in Norway since 1986. The BRIS reporting system was put into operation in January 2016. BRIS is an abbreviation for "fire, rescue, reporting and statistics". The data collected in BRIS is used both by the fire brigade and others who work with fire prevention. *Brannstatistikk.no* is an open web-based service from DSB that was launched in a beta-version in November 2019. The service provides an overview of all callouts to the fire and rescue service throughout Norway since 2016.

2.1 Building fires with electrical cause

A report summarizing the fire statistics for 2018 is available on DSB's website [1]. Of a total of 5089 registered assignments in 2018 related to building fires, 3537 assignments (approx. 70 %) were related to dwellings. The source of fire for the dwelling fire callouts is distributed as shown in the pie chart in Figure 1 [1]:

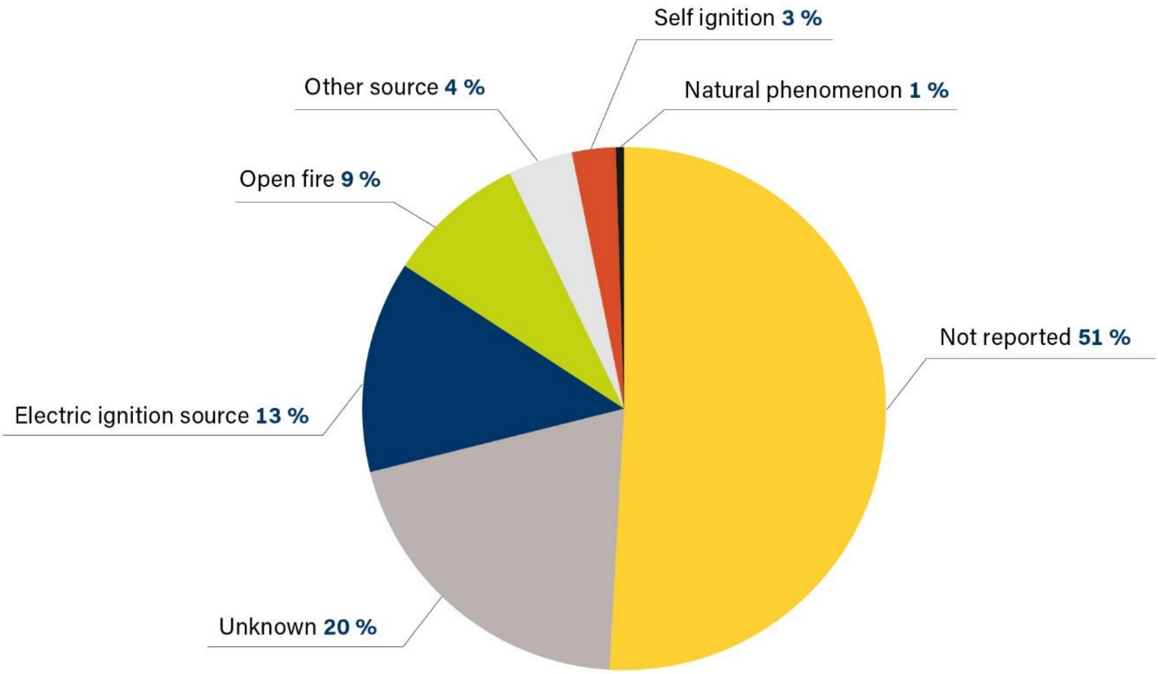

Figure 1: Distribution of fire sources for dwelling fires in the period 2009 - 2014 [1].

An immediate comment on these statistics is that underreporting is very high, and there is therefore reason to question whether the underlying data is particularly good, since it cannot be assumed that the unknown and unreported causes are distributed in the same way as the fires that have had a specified cause established. The categories "not reported" and "unknown" account for more than 70 %, which unfortunately means that the statistics are not very suitable for finding complex causal relationships. Possibly the statistics can be useful for capturing trends. In any case, Figure 1 shows that the number of dwelling fires with an electric ignition source will be statistically significant and constitutes a substantial proportion.

There are also corresponding international fire statistics where the proportion of registered building fires with electrical causes can be extracted. Table 3 summarizes the percentage of all registered building fires caused by electrical causes in selected countries and regions.

Table 1: Proportion of building fires with electrical causes in different countries in the specified period [2]-[4].

Country	Proportion	Period
Norway	21 %	2008-2013
European Union	13 - 20 %	2004
United States	5 - 18 %	2009-2011
Great Britain	18 %	2010-2020
Germany	33 %	2002-2013
China	27 %	2005-2010

An immediate comment to the numbers presented in Table 1 is that it does not appear that the proportion of fires with electrical causes is significantly different in Norway compared to the proportion registered in other, relevant industrialized countries, including the neighboring countries Sweden and Denmark. This has also previously been pointed out in a SINTEF report from 2007 [5], where the number of fires in installation materials in low voltage electrical systems was examined. In the ten-year period from 1995 to 2004, it was found that fires in installation materials accounted for approximately 7 % of dwelling fires in Norway, while the corresponding figures for England and the USA were 6 and 9 % respectively. Furthermore, DSB's fire statistics showed that wires and cables cause most fires in installation materials, where the incidence is approx. 30 – 40 %, followed by socket materials and junction boxes/clamps. Cables are the electrical installation material that causes by far the majority of dwelling fires in Norway and the United States, nearly 50 % [5].

The second largest single cause of dwelling fires in Norway is power lines and cables, which caused an average of 21.4 fires per year in the period 2009 - 2013 [6]. In other words, fire statistics suggest that between 1 – 2 % of dwelling fires in Norway start in electrical cables. This is about the same proportion reported in Danish and Swedish fire statistics [4]. It has also been pointed out that there are no fire statistics available that provide insight into how electrical cables contribute to the spread of fire after a building fire has occurred [4].

2.2 Definition clarification for series arc and series faults

In DSB's fire statistics, fires with electrical causes are divided into eight subcategories, and in the period 2009 – 2014 the distribution of these was as shown in Figure 2 [7].

Here it can be added that DSB's definitions of series arc, short-circuit arc, earth fault and creep current are the following [8][9]:

- ***Series arc*** *is caused by poor contact in a connection. Contact failure results in locally higher resistance with subsequent heat generation and can lead to a standing arc. This can lead to burning or ignition of insulation material, resulting in a fire*.
- ***Short-circuit arc*** *or parallel arc is an electrical discharge between two conductors that causes an arc. Usually, the circuit breaker will activate, but situations may arise where this does not happen.*
- ***Earth fault*** *means that one or more phase conductors have an accidental or unwanted connection to earth, for example to metal enclosures on equipment or metal screens in cables*.

- ***Creep current** is electricity going astray. Due to poor cleaning (dust, oil spills, etc.) and lightning surges, unwanted current paths can form towards earth or between live conductors with heat generation as a result.*

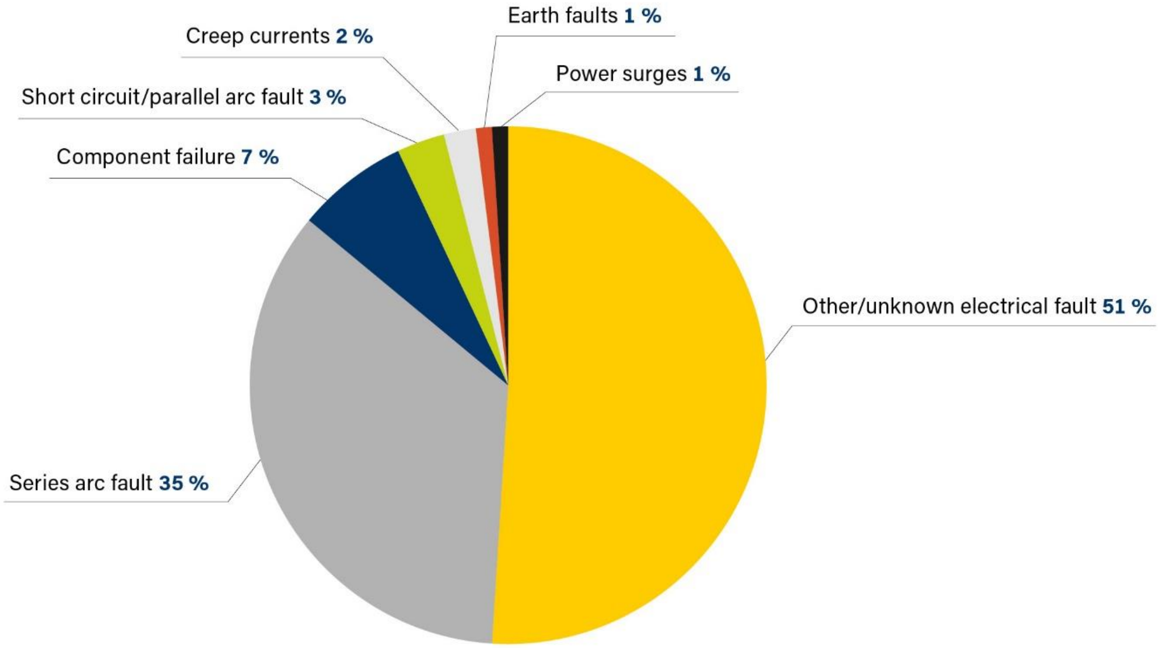

Figure 2: Distribution of causal categories for dwelling fires with electrical causes in the period 2009 - 2014 [7].

In the category **Other/unknown electrical cause** both fires where the cause (unknown cause) is recorded, beyond the fact that it is due to electrical cause, and fires with a cause that is not covered by the defined subcategories (other cause). In Norway, series arcing is the largest causal category for dwelling fires with electrical causes. The proportion is high and is around 35 - 50 % [5], and it hasn't changed appreciably over the last two decades. Therefore, there does not appear to be any trend in one direction or the other based on the registrations in the fire statistics over a relatively long period. It is unclear why the causal category "series arc" constitutes a relatively large proportion of fires with electrical causes in the Norwegian fire statistics. As mentioned earlier, this may be related to the design of the registration forms and the definition DSB has chosen for the series arc [10]. It has also been speculated that there may be special Norwegian circumstances that make this category of causes so large. Among the conditions that have been mentioned are the following [5]:

- The power grid is unique (IT/TN network).
- A lot of wooden buildings.
- Electricity is used for heating and can cause continuous high loads in electrical circuits.
- Inadequate fire investigation.
- Different interpretation of electrical faults.
- High failure rate in electrical systems.

In the five-year period 1999 - 2003, similar fire statistics from the USA show that only 6 % of fires in low voltage electrical installations in dwellings had a series arc as the registered cause of fire, while 47 % were due to a short-circuit arc [5]. In other words, there is a relatively large difference in the size of the causal category *Series arc* in the Norwegian and American fire statistics. It can be added that the power grid in the United States and Canada has 120 V AC voltage (60 Hz), while in Europe it has 230 V AC voltage (50 Hz). The electricity load in electrical installations will therefore typically be greater in the US than in Europe. Consumption patterns can otherwise be assumed to be fairly similar in these two regions.

DSB's definition of series arc almost states that contact failure (series fault) is the same as series arc. It may be questioned whether this is appropriate. There is no good scientific basis for saying that all series faults result in series arcs. As early as 1992, Sletbak commented that fire causes registered as series arc are most likely the same phenomenon that other countries register as glowing contact connections [11]. SINTEF NBL has pointed out the same in several reports [5][12][13]. Here it is written, among other things [12]:

- *"When a fire has occurred in a dwelling, and the fire investigators observes heat generation in an electrical connection near the ignition point, it is usually concluded that the cause of the fire is electrical failure resulting from series arcing."*
- *"In an analysis of DSB's fire statistics for the ten-year period 1995 - 2004, it was found that 50 % of fires in electrical installation materials in general and 57 % of fires in sockets are registered with series arc as the cause of fire."*
- *"By comparison, similar statistics from the USA (NFPA), based on more than 19.000 fires per year that have started in installation materials in homes in the five-year period 1999 - 2003, show that only 6 % of the fires had series arc as the cause of fire, while 47 % of the fires had various forms of short circuit as the cause of fire."*
- *"The above figures clearly indicate that we have not understood the actual cause of heat in installation materials, and that such faults are interpreted differently."*
- *"Series arc is rarely mentioned as a cause of fire in other countries (USA, Japan, England, Canada). Heating in electrical material is explained by the formation of copper oxide at the connection point. This causes increased resistance and heat generation, so that eventually it begins to glow with temperatures in the range of 1200 - 1300 ℃."*

Furthermore, a Norwegian study from 2012 points out the following [14]:

- "*Series arcing in the context of fire is therefore highly likely the same phenomenon that other countries register as glowing contact connection. Since both series arc and glowing contact connection are typical series faults, and both are due to contact failure, there are strong indications that they are registered as the same fault".*
- "*The main problem with series faults in electrical installations is probably mainly glowing contact connections, and not series arcing*."

In this report, therefore, the series arc will be considered to be part of the course of a series fault. In the next chapter, the term series fault will be described in more detail. Statistics related to series faults and cable fires will be further commented on in Chapter 5.4.

3 Series fault in a low voltage electrical installation

Fire statistics suggest that series faults are a frequent cause of fire in low voltage electrical installations. A series fault can be termed as a poor electrical connection and is also often called contact failure. A series fault has a great potential for damage in cases where the current load is high in a poor or weakened electrical connection. The main challenge with a series fault is that the current in the circuit is not significantly affected by such a weakened electrical connection, which means that conventional safety devices, such as earth leakage circuit breakers, are not able to detect the fault and disconnect the power supply to the course. The outcome of a series fault may be dissipation of electrical energy with subsequent heat generation and local overheating, which entails a high risk of ignition of surrounding combustible material and subsequent fire. In other words, a series fault causes electrical energy to be converted into thermal energy.

3.1 Sequence of events for a series fault

To understand how a series fault can develop into a fire, it is important to clarify the actual sequence of events. Figure 3 shows a simple sketch intended to illustrate the connections between the various concepts included in the phenomenon description. A series fault is thus a weakened electrical connection that can occur for various reasons. The fault causes an electrical barrier (resistance) that affects the current flow at the point where the fault has occurred. The subsequent sequence of events is complex and dynamic, with different stages that can occur in different sequences and at the same time influence each other. The various stages of the sequence of events will be described in the following [10].

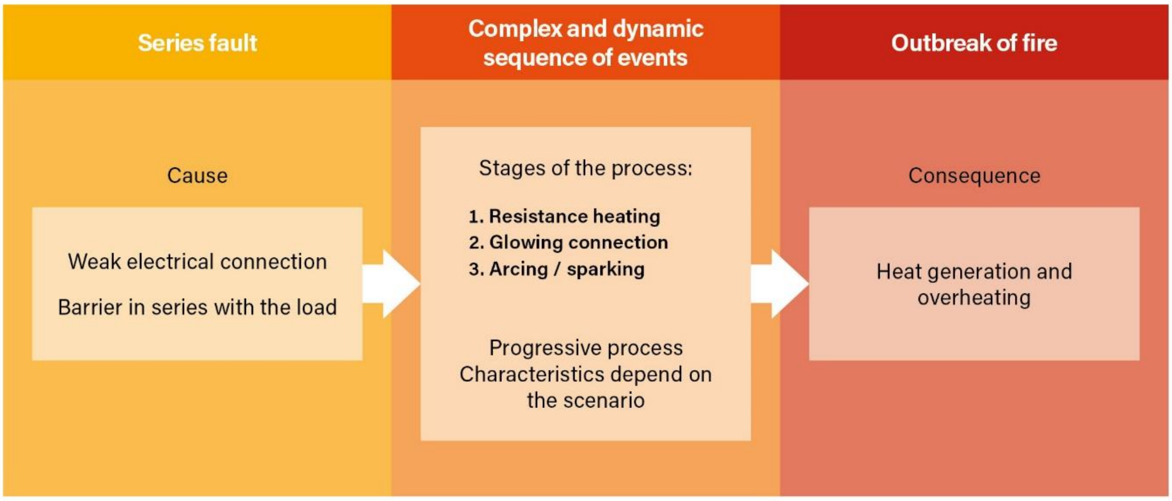

Figure 3: Illustration of the course of a series fault from the formation of a weakened electrical connection (cause) to the ignition of a fire (consequence) [10].

3.1.1 Resistance heating

A poor or weakened electrical connection will result in increased electrical resistance and this elevated electrical resistance may cause local heating when there is a significant current load. The increase in temperature can speed up a process that involves oxidation and seepage of metal. An oxide coating, for example, in the form of a Cu_2O layer, can form and spread on the surface of the metal conductor, causing current to pass through this coating. Most metals, including copper, aluminum, and various iron alloys, can form an oxide coating. The oxide coating has significantly higher electrical resistance than the metal and the outcome is a process that is self-reinforcing or progressive, where the temperature continues to increase because the oxidation of the metal conductor increases. Such a contact point can potentially generate a heat corresponding to 30 – 40 W at an amperage of 15 – 20 A through the contact point [5]. There are also other causes of resistance heating in an electrical installation, including: [5]:

- Too much insulation.
- Heavy overload.
- Leakage current and earth faults.
- Overvoltage/voltage surges, e.g. from lightning strikes or equipment failures.

3.1.2 Glowing connections

In a weakened electrical connection, the heat generation can become so large that the connection becomes glowing. The reason for this is that high power dissipation can occur in a relatively limited area (point). The relationship between temperature, resistance, current and voltage in a weak electrical connection when applying alternating voltage is summarized in reference [6]. The formation of an oxide layer is necessary for glowing to occur, and such a layer may initially be formed by an arc [2]. Sletbak et al. studied Cu_2O formation and found that this oxide layer (filament) glowed at 1200 – 1300°C, which is a sufficiently high temperature to ignite most common combustible materials [11]. The reason why the current is narrowed in a thin filament in the surface of the oxide layer is due to the fact that the oxide has a negative temperature coefficient. They further found that current could be concentrated in such a filament already at an amperage of 0.15 A, and that power dissipation depended on the amperage and age of the filament. In their case, they measured a power dissipation of 17 W at 1 A [11]. In other studies, it has also been observed that glowing connections can occur at relatively low currents, around 0.15 – 0.8 A [15]. Glowing connections can last for hours and days without interruption and can resume after a power outage. They do not necessarily need to develop into a series arc, as deformations (partial melting) of insulation materials can also occur that can lead to a short circuit or current leakage to earth. These cases will normally be detected by an earth leakage circuit breaker, which will interrupt the further process.

It has been pointed out that if one considers a series fault as a chain of many fault situations, the glowing connection fault usually occurs at the beginning of the chain, and rarely at the end of the chain [2]. It has also been pointed out that a glowing connection can charred insulation materials in the immediate vicinity, which can contribute to the formation of a stable arc, which in turn increases the likelihood of ignition and development of a fire [2].

3.1.3 Series arc

A series arc can be seen as part of the course of a series fault. An arc is defined as *"light discharge of electricity over an insulating medium, usually accompanied by partial evaporation of the electrodes"*, according to International Electrotechnical Vocabulary (IEC 60050). Arcing in this context occurs when a weakened electrical connection is obtained between live parts (electrical conductors or connection point), which causes a spark or standing lightning-like arc with a very high temperature in the air space around the connection. The primary difference between a spark and an arc is that a spark is a transient phenomenon, whereas an arc will have a certain duration [5]. In an electrical installation, arcing is undesirable and potentially dangerous, but there are also a number of consumer equipment that generates (desired) arcs as part of its function, such as electric brush motors found in vacuum cleaners and electric drills, among others.

Arcing in a low voltage electrical installation can occur in different forms, and a distinction is often made between a series arc and a parallel arc. The illustration in Figure 4 shows the difference between these three types of arcing. A series arc occurs in series with the load (Figure 4a), while a parallel arc can occur between the installation's phase conductor (L) and neutral conductor (N) in parallel with the load (Figure 4b) or between a conductor and earth (Figure 4c). In general, parallel arcs are more risky than series arcs because the energy in the arc is significantly greater, and can often occur explosively with the consequence that separated parts of the metal conductor are more likely to come into contact with combustible material [5].

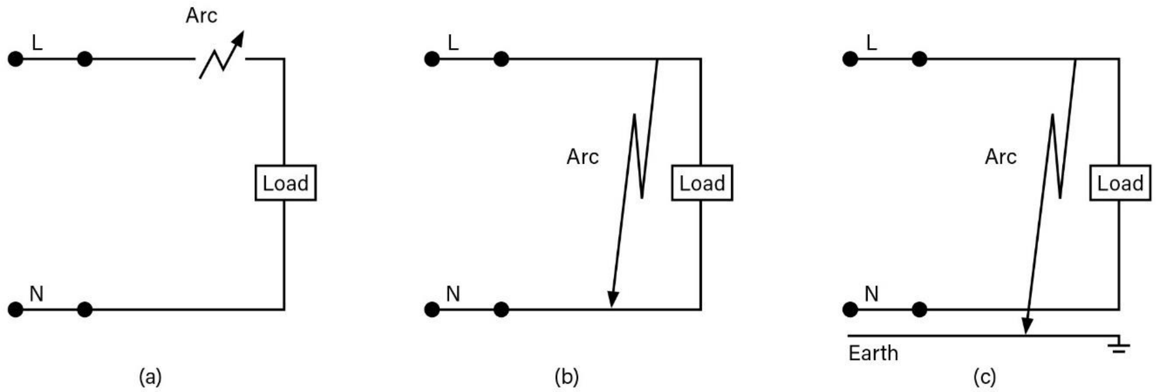

Figure 4: Different types of arcing that can occur in an electrical installation. (a) Series arc, (b) parallel arc, (c) earth fault arc.

Arcing can have many origins, but the three main reasons why arcing occurs in an electrical installation are [16]:

1. **Short circuit.** This occurs when there is a sudden reduction in impedance, often as a result of two current-carrying metallic conductors coming into contact with each other. In general, the current in a short circuit arc is inversely proportional to the impedance of the conductors.

2. **Outer ionization of the air**. In air at normal atmospheric pressure, it is difficult to establish arcs at 230 V alternating voltage because the dielectric strength of air is 3 MV/m under these conditions. If a plasma of ionized gases is formed in the air, the dielectric strength of air can be significantly reduced. Arcing or flames can be sources of such plasma formation. If such ionized gas is transferred to other parts of the installation where voltage is applied, additional arcs can be created. It has been argued that arcing can hardly occur in 230 V electrical installations without the atmosphere having already been ionized, either from existing/nearby arcing or a fire. Fire-induced arcing in the electrical installation is considered to be the most common trails of arcing found by fire investigators at the scene of the fire [5].

3. **Charring of the insulation**. Moisture and contaminants on the surface of the insulation material can cause leakage currents and over time this can create a carbonized path in the insulation because of a thermal decomposition process. Charring can also occur as a result of external thermal influence. The formation of carbonized paths will be strongly dependent on the type of polymer. Polymer materials with a high carbon-to-hydrogen ratio (C/H), especially with aromatic compounds, more easily produce carbonized path [17]. Continuous arcs can occur in a low voltage electrical installation due to the formation of a carbonized path in the insulation between two conductors. This charring process will be described in more detail in the next chapter.

An example of a sequence of events that has been observed for a series fault is as follows [18]: In the case of a newly formed arc, it has been observed that at the start (in the sparking phase) a discharge occurs, which generates white noise (i.e. equal strength for all frequencies). Eventually, the low and high frequency noise disappears as heat generation continues and this discharge eventually transitions to a glow phase, with a glowing current path in the oxide layer that develops from one electrode's metal surface to the other electrode's metal surface. Current paths extending several centimeters have been observed [11][18]. During the glowing phase, both the length and thickness of the oxide layer increase. In the gap between the electrode, the void is filled with copper oxide. At the same time, metallic copper retracts from the electrodes. This process etches away the electrodes some distance from the fault location, which means that there is a transport of material towards the connection. The result is the accumulation of a thick oxide layer around the electrodes at the connection. Eventually, the current path along the oxide layer becomes so long that the ability to conduct current in a glowing filament in the oxide layer cannot be maintained. Two options for the further course are then observed:

- It is no longer possible to conduct a current when applying 230 V, i.e. the fault location remains insulating until a voltage surge (pulse) manages to re-establish the conduction of current.
- A condition occurs where the voltage across the fault location is about 0.5 V. In comparison, in the case of ohmic contact the voltage across a fault location will normally be around 20 mV. The heat generation may be low (on the order of 1 W), implying that such a condition may be of a long-term nature, provided that something does not happen that changes the conditions at the connection (current load, mechanical stresses, breakage, corrosion).

The formation of various forms of arcing in the course of a series fault is therefore largely dependent on electrical parameters, initial conditions, and earlier stages in the process, such as resistance heating and glowing. Four different ways in which a series arc can occur in a low voltage electrical installation have been described [5]:

1. When current carrying electrodes are separated from each other, an arc is formed. The arcing stops if the distance becomes too great. Arcs can be created this way, even at a low voltage. For example, mechanical vibrations can cause a motion that causes the electrodes to be temporarily separated from each other, which can create small arcs between the conductors. For a multi-threaded cable, one or more strands of wire may break internally near the cast strain relief from repeated pulling in the wire or from mechanical clamping or cutting [19].
2. Arcing can occur when the electrical voltage across two electrodes becomes higher than the breakdown voltage of the material separating the electrodes. A spark may then form between the electrodes that could develop into an arc if current and voltage are sufficiently high.
3. A glowing contact connection between the electrodes can lead to arcing.
4. With the formation of a carbonized path between the electrodes, arcs may form that make their way around this carbonized path. This phenomenon will be elaborated on in Chapter 4.

3.2 Research in Norway and internationally

Several reports have been published by SINTEF NBL (Norwegian Fire Research Laboratory) on topics relevant to series faults in low voltage electrical installations. DSB has been the client for many of these reports.

- Fires due to electrical installation materials, Report NBL A06121, 2007 [5].
- Fire due to electrical fault in installation materials and low temperature heat exposure from lighting, Report NBL A08120, 2008 [12].
- The development of fire damages in Norway - measures to reduce fire damages, Report NBL A08111, 2008 [13].
- Analysis of DSB's fire statistics for building fires in the ten-year period 1994-2003, Report NBL A04122, 2004 [20].
- The development of fire damages in Norway compared to other Nordic countries – Causes of differences, Report NBL A06116, 2006 [21].
- Incidents involving fires in electrical installations, Report NBL A12137 [22].

- Heat generation in electrical equipment as a source of ignition in buildings, Report NBL A06122, 2007 [23].
- Electrical cables and fire risk, Report NBL A12123, 2012 [24].

Relevant international literature published over the past two decades includes the works of Vytenis Babrauskas, Jean-Mary Martel, and John J. Shea:

- **V. Babrauskas** has published several books and a number of scientific journal articles on topics related to the causes of fires occurring in low voltage electrical installations [17][25][26]. Babrauskas founded Fire Science and Technology Inc. (FSTI) in 1993.
- **J. M. Martel** published his PhD thesis titled "*Series arc faults in low-voltage AC electrical installations*" in 2018. The thesis covers many years of research on the phenomenon of arcing in low voltage electrical installations and methods for arc detection in the form of arc protection [2]. The work had three defined objectives: 1) Understand how series arcs in low voltage electrical installations can result in fires, 2) Explore the possibilities for reducing the occurrence of series arc faults by implementing passive measures, and 3) explain the origin of the trigger characteristic of arc fault detection devices and evaluate the level of protection such devices provide. Martel has been affiliated with Siemens AG for over 15 years.
- **J. J. Shea** has published many research articles on topics related to the causal relationships for fires that occur in low voltage electrical installations [27]-[29]. Shea has been affiliated with Schneider Electric Company and Eaton Corporation since 1993.

4 Insulation materials for electrical cables

Electrical insulators are materials with low electrical conductivity, which prevents current flow in the material. This property makes it possible to isolate electrical conductors from the environment so that unwanted currents do not arise in an electrical installation. An electrical cable will typically consist of several metallic conductors and the role of the cable insulation material is primarily to isolate each conductor from the other conductors and the environment. Cable insulation materials generally have a number of different technical requirements, including:

- Dielectric properties: The material must provide good electrical insulation.
- Fire properties: The material should be fireproof and/or self-extinguishing.
- Chemical resistance: The material should be able to withstand chemical degradation from various substances.
- Temperature range: The material must withstand temperatures in its intended operating range.
- Flexibility: The material must not be too rigid, which makes installation difficult.
- Durability: The material must withstand external influences, including mechanical wear, humidity, temperature fluctuations and light exposure.

4.1 Historical development

Today, almost all insulation materials for electrical cables are made of plastics. Historically, natural fibers and natural rubber were used, but both have over time been replaced by various synthetic materials, including silicones, rubber, plastics, and fibers. Figure 5 shows a timeline of some relevant milestones in the development of electrical cables and insulation materials.

Year	→	Milestone
1830	→	Telegraph line introduced
1858	→	Transatlantic telegraph line is established
1880	→	Natural latex used as cable insulation
1882	→	Bast fiber used as cable insulation
1897	→	Rubber used as cable insulation in 11 kV transmission line
1933	→	PVC cable insulation developed in Germany
1942	→	Polyethylene cable insulation developed
1950	→	PVC cable insulation commercialized
1970	→	PEX cable insulation commercialized

Figure 5: Timeline of some milestones in the development of electrical cables and insulation materials.

The most prevalent plastic materials in today's cable market are PVC and polyethylene. These are both classified as thermoplastic, which means that the molecular chains that make up the material are separated when exposed to heat. Among other things, this property allows thermoplastic materials to be melted and transformed repeatedly. Another type of plastic material is classified as thermoset plastic, where the material is subjected to a curing process that is often done by irradiation, heat or through a chemical reaction. This hardening means that the molecular chains are bound to each other, which means, among other things, that the material cannot be melted or transformed. Cross-linked polyethylene (PEX) is an example of such thermosetting plastic.

4.2 Cable construction

Figure 6 illustrates the structure of a modern electrical cable in a low voltage electrical installation, often referred to as an installation cable. The cable is constructed of at least the following elements:

- Flexible conductor (single-wire, multi-threaded or multi-wired) made of copper or aluminum
- Conductor insulation of plastic (polymer material)
- Plastic filler sheath
- Plastic outer sheath

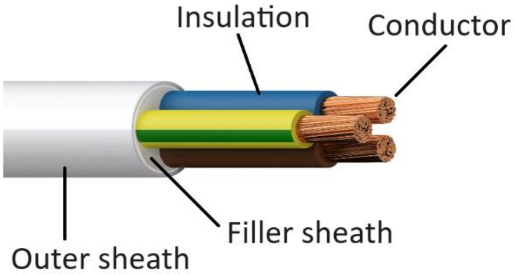

Figure 6: Typical design for a 230 V AC installation cable with two phase conductors and one earth conductor.

In general, the cross-section of the metallic conductor will determine how much current can be passed in the conductor, while the thickness of the insulation material will depend on the type of material and the voltage between the phase conductors. In this report, the term PVC insulated electrical cable will refer to a cable for which the insulation material for the conductors is PVC, while not specifying what the sheathing material is made of.

4.3 PVC

PVC (polyvinyl chloride) is one of the world's most widely used polymer materials and has a wide range of applications. PVC production in the EU in 2019 was around 6 million tons, with net exports of around 1 million tons. 10 % of all plastics used in the EU are PVC and Figure 7 shows the use of PVC in the EU by different applications in 2017. The pie chart shows that around 67 % is used in the building sector, while 7 % (0.35 million tons) is used in electrical cables. Global use of PVC in electrical cables in 2018 was approximately 3.6 million tons [30]. PVC is a very common insulation material in low voltage electrical installations, and in the United States, for example, PVC makes up about 2/3 of the insulation material used in electrical cables in buildings [17]. PVC has historically also been used in other installation equipment in low voltage electrical installations, including junction terminals, junction boxes, encapsulations, plugs, connectors, and corrugated plastic pipes. For many of these components, PVC plastic has been phased out and replaced by halogen-free plastic.

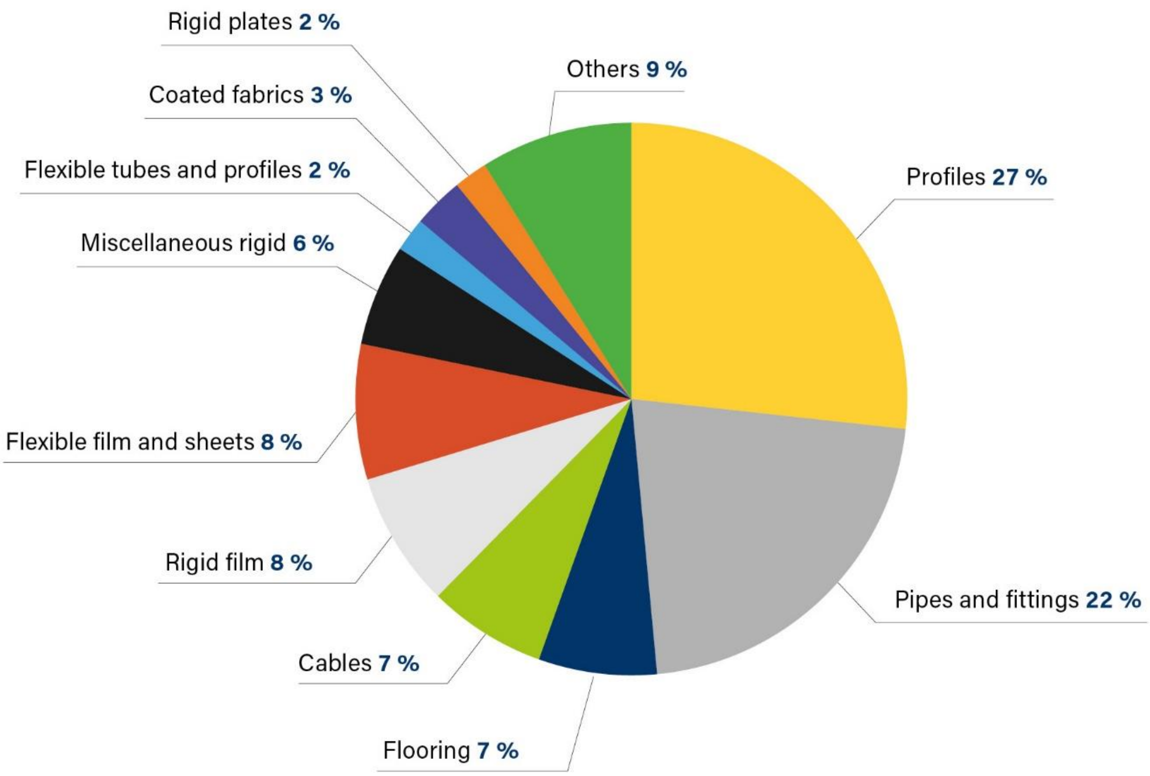

Figure 7: Use of PVC in the EU in 2017 by different applications [31].

One of the main reasons for the widespread use of PVC is that it is easy and cheap to produce, where the raw materials are table salt (NaCl) and hydrocarbons in the form of natural gas or oil. PVC is a polymeric material, which means that it consists of a repeating structural unit, a so-called monomer, which is connected by a covalent chemical bond. Figure 8 shows this structural unit for PVC. The monomers bind to each other to form long-chain molecules (polymers). It can be mentioned that the monomeric vinyl chloride (C_2H_3Cl) contains 57 % chlorine by weight and is classified as carcinogenic to humans (Group 1 carcinogen).

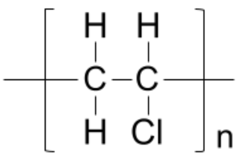

Figure 8: Structural unit (monomer) of PVC polymer material.

In general, a number of additives are utilized to improve and tailor the properties of the plastic. In most cases, the additives are not chemically bound to the plastic polymers, but an exception may be some type of flame retardants [32]. PVC for use as a cable insulation material is mixed with up to 50 % additives to obtain suitable properties, and the formulation for PVC used as insulation material in electrical cables will typically be the following [33]:

- 52 – 63 % PVC resin.
- 25 – 29 % plasticizer (phthalate or trimellitate).
- 5 – 16 % filler ($CaCO_3$ or kaolin).
- 2 – 4 % stabilizer (zeolite).
- 0.2 – 0.3 % wax.

In addition, smaller amounts of dyes, lubricants, antioxidants, and fire retardants are added [17]. The main role of the plasticizer is to prevent thermal degradation of the insulating material, in addition to making it pliable, while stabilizers are added to reduce discoloration, aging and decomposition of hydrogen chloride [5]. For example, light stabilizers may be added to reduce the separation of hydrogen chloride resulting from exposure to ultraviolet light. The filler has several functions, including trapping (scrubbing) decomposed hydrogen chloride gas and optimizing the dielectric properties of the insulation material.

4.4 PEX

Polyethylene is a thermoplastic material produced by the polymerization of ethylene gas, derived from either petroleum gas or natural gas. Polyethylene is the most widely used plastic material in the world and is used, among other things, in packaging, bottles, bags and containers. Polyethylene, like PVC, can be formulated with various additives to tailor its properties with regard to its application. Low density polyethylene (LDPE) is used, among other things, for flexible products. Linear low-density polyethylene (LLDPE) is a variant of LDPE that is softer and more pliable and is often used in cable insulation material. High density polyethylene (HDPE) is used for products that require rigidity/strength, such as pipes. When polyethylene is converted to thermosetting plastic, it is referred to as cross-linked polyethylene, often abbreviated PEX, XLPE or XPE. The curing process means that PEX has good thermal and mechanical properties, making it a durable polymeric material with a long service life. In general, hardening leads to increased compression strength, tensile strength, thermal stability and water absorption resistance [34].

The repeating structural unit (monomer) of polyethylene is shown in Figure 9a. The monomer forms long-chain molecules in the same way as PVC, where the only difference is the incorporation of the halogen (chlorine), which results in PVC having substantially more mass and higher mass density than polyethylene. Electrical cables that do not contain the elements fluorine, chlorine, bromine, or iodine (group 17 in the periodic table) are often called halogen-free cables. Figure 9b shows the binding structure of PEX. The long-chain molecules for PEX have a cross-linking that makes it more stable compared to polyethylene, as shown in Figure 9c. This cross-linking can be done either physically or chemically: physical cross-linking involves exposing the polymer material to high-energy electron or microwave radiation (PE-Xc), while chemical cross-linking involves the addition of chemicals or initiators such as azobenzene (PE-Xd), silane (PE-Xb) or peroxide (PE-Xa) to create free radicals that allow this cross-linking to form.

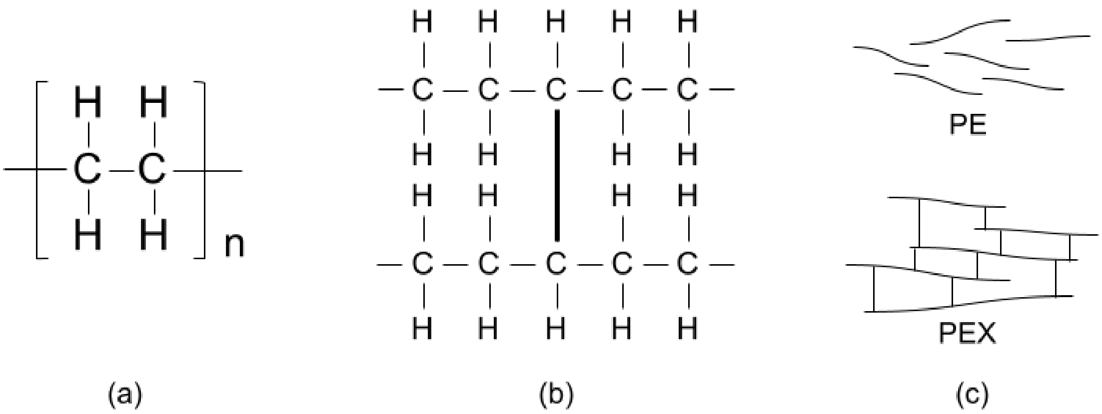

Figure 9: (a) Structural unit (monomer) of polyethylene (PE), (b) bonding structure of cross-linked polyethylene (PEX), (c) layered structure of PE and PEX long-chain molecules.

Polyethylene itself has excellent dielectric strength, high insulation resistance and low dielectric dispersion factor at all frequencies which makes it a very good insulator material, but it has a limited temperature range due to its thermoplastic properties. The cross-linking means that PEX has a much larger temperature range while maintaining its good dielectric properties. Table 2 compares various relevant properties for PVC, polyethylene and PEX cable insulation material [35]. In most categories, PEX has better properties compared to PVC. The good thermal properties mean, for example, that a PEX insulated installation cable in a low voltage electrical installation can be specified for a conductor temperature up to 90°C. Often, a PVC insulated cable will be limited to 70°C conductor temperature, which indirectly means that a PEX insulated cable can conduct a higher current for a given conductor cross-section. The good dielectric properties mean that PEX is very often used as insulation material in high voltage cables.

The additives for PEX cable insulation material will typically be as follows [36][37]:

- 60 – 80 % polyethylene resin (LLDPE).
- 20 – 40 % flame retardants ($C_{12}Br_{10}O$, $C_{12}H_2Br_8O$, Sb_2O_3, $Al(OH)_3$).
- 2 % antioxidants (butylated hydroxytoluene, poly(1,2-dihydro-2,2,4-trimethylquinoline)).
- In addition, smaller amounts of dyes and stabilizers are added.

It can be added that commercial recycling of PEX is challenging due to technical and economic reasons. Typically, PEX will degrade before it melts because it is cross-linked (hardened). There are methods for breaking up the cross-links, but these involve techniques that are costly. Most of this plastic material is therefore currently sent either to landfill or incineration, resulting in land pollution and CO_2 emissions [38].

Table 2: Comparison of different properties of PVC, PE and PEX cable insulation material [35].

Property	PVC	PE	PEX
Mass density [g/cm3]	1.4	0.92	0.92
Maximum Temperature [°C]	60 - 70	75	95
Softening temperature [°C]	120	110	127
Instant short-circuit temperature [°C]	135	150	250
Insulation resistance [mΩ·K/m]	20	1000	1000
Volume resistivity [Ω·cm]	1e12 – 1e15	1e17	1e17
Dielectric strength [kV/mm]	20 - 35	20 - 35	35 - 50
Dielectric constant (60 Hz)*	6 - 8	2.3	2.3
Dielectric loss (60 Hz)	1e-1	1e-4	1e-4

* Lower dielectric constant means lower losses at high-frequency signal transmission

4.5 Decomposition and charring

4.5.1 PVC

The thermal degradation mechanisms of PVC have been studied in depth since its introduction over 70 years ago. For PVC based cable insulation material the various additives will constitute up to 50 % of the mass, and thus, the formulation of additives will have a major impact on the thermal degradation. Babrauskas has previously presented relevant findings related to the decomposition processes of the PVC formulations typically used in cable insulation material, and the most significant relationships are as follows [17]:

- When PVC is heated, it is relatively susceptible to decomposition and charring (carbonization) compared to other polymer materials, such as PEX. When the temperature is increased above room temperature, HCl molecules are released (dehydrochlorination), and a polyunsaturated material is left behind, which is sometimes referred to as polyacetylene.

- HCl (hydrochloric acid) is a highly corrosive gas that attacks and dissolves metallic conductor materials in low voltage electrical installations and electronic components.
- Already in the temperature range 60 - 80°C, outgassing of HCl will be initiated, and at 360°C HCl will be completely removed from the polymer matrix. The filler $CaCO_3$ is added to capture HCl gas and thus reduce outgassing. For pure PVC, complete dehydrochlorination is achieved at about 250°C.
- The dehydrochlorination process is autocatalytic, i.e. the HCl gas promotes/amplifies the reaction. When further heated to 350 – 500°C, several parallel reactions will occur, including the production of polyenyl macroradicals, dehydrocyclization, aromatization, and chain scission, so that one eventually ends up with a cross-linked charred (hydrocarbon) residue. Figure 10 shows an illustration of fractures in the polymer chain and the formation of charred material when PVC is heated [39].
- Similarly, the plasticizer will start to evaporate already at 85°C. When heated to 130°C for 24 days, it has been shown that 25 % of the plasticizer disappeared from the polymer matrix. Plasticizers, in general, have a negative effect on the stability of PVC. Loss of plasticizer can lead to brittleness and cracking.
- When heating the cable insulation material, phthalates can begin to decompose at temperatures as low as 105°C and release gas compounds which, when combined with the oxygen in air, form an ignitable gas mixture. High temperatures, such as from glowing connections or series arcs, can lead to further degradation of these gas compounds to form less complex but still highly flammable gases in the presence of oxygen. For most pure hydrocarbons in air, the self-ignition temperature ranges from 240 - 540°C, which is far below the reported temperatures (1230°C) for glowing connections [19].

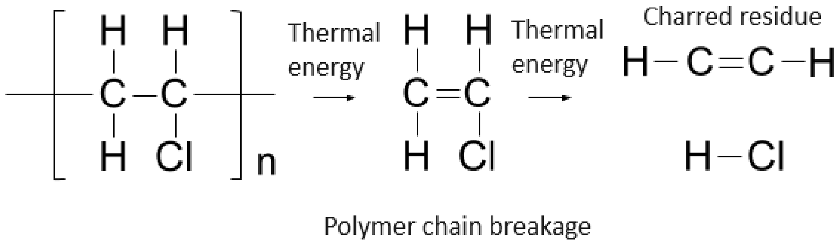

Figure 10: Illustration of the polymer chain breakage and the formation of charred residue and HCl when PVC is exposed to thermal energy [39].

Some additives, such as the filler $CaCO_3$ and the flame retardant Sb_2O_3, can be converted to ash during combustion, and this ash does not contain carbon. The formation of such ash in the (charred) polymer matrix is a phenomenon that delays or inhibits sustained combustion. A certain fraction of the polymer material remains in ash form and allows less volatile and flammable fuel to be released (in the form of gas). The ash can also act as a barrier between the external heat source and the polymer material, thus reducing heat propagation to intact parts of the polymer. In addition, the higher viscosity (increased firmness) of the mesophase with charred solid residues can inhibit the transfer of ignitable fuel from the decomposed polymer to the surrounding air. The formation of charred material is a strategy used by the manufacturer to improve its fire resistance properties [2].

This thermal decomposition of PVC greatly affects the dielectric properties, and the most significant interrelations are as follows [17][19]:

- The dielectric strength of PVC formulations used in cable insulation material is typically 24 – 36 MV/m, compared to around 350 MV/m for pure PVC at room temperature. This decrease in dielectric strength can be caused by uneven distribution of the filler, which breaks up the insulating ability of the polymer material. In addition, there may be small air pockets (defects) in the polymer matrix that create irregularities in the electric field and intensification of field strength in the boundary layer between the void and the polymer. In comparison, air has a dielectric strength of 3 MV/m.

- Decomposition of PVC causes the dielectric properties of the material to deteriorate, and it gradually becomes semiconducting. At about 160°C, the material becomes semiconducting under short-term exposure (about 10 hours), while prolonged exposure (about 1 month) can cause faults at temperatures as low as 110°C. The charred material is a temperature-dependent semiconductor that can lead to breakdown across the interface at voltages lower than 115 V_{rms}.
- Elevated temperatures will weaken the dielectric properties of PVC, as the loss of plasticizer causes the formation of small voids in the material, which will reduce the dielectric strength. This ratio is governed by the amount (and type) of plasticizers used. For PVC without plasticizer, the dielectric strength rises slightly up to 70°C, but then drops steeply with increasing temperature.

There are also factors other than elevated temperature that affect the dielectric properties of PVC. These can be characterized as degradation as a result of aging and can generally be divided into three main categories [17]:

1. **Electrical aging**. This phenomenon is also called voltage-induced degradation where a local dielectric breakdown (partial discharge) occurs. In particular, the formation of tree-like channels in the insulator (treeing) is of significant importance for cable insulation materials in high voltage applications, and this will be described in more detail in the next section.
2. **Physical aging**. Oxidation of the polymer can lead to brittleness and cracking, which may affect the field strength of the insulator in the same way as small air pockets described earlier. Mechanical stress applied over time can lead to the formation of polymer radicals and create microvoids in the polymer material.
3. **Chemical aging**. The formation of free radicals leads to bond breakdown (unzipping) of the polymeric structure. The process can be started thermally or mechanically, by oxidation reactions, by hydrolysis, or by UV/ionizing radiation. It has been shown that metals can accelerate oxidative pyrolysis of polymers used in cable insulation materials. For example, zinc dust has been shown to have a harmful effect on PVC. Highly polluted environments can correspondingly lead to degradation of the polymer material.

The phenomenon of tree-like channels forming in insulator materials has been extensively studied in recent times. Figure 11 shows this phenomenon where tree-like channels are formed in PEX cable insulation material [40]. Such propagating channels are a kind of precursor of dielectric breakdown for the insulator, and the phenomenon is often divided into three different types [17]:

1. **Electric**. Local dielectric breakdown (channels) forms as a result of applying a high electric field over a long period of time. Impurities, cavities, and mechanical defects in the polymer material can cause an electric field that is critically high in a localized area. This can form ionized gases in cavities in the material, which in turn can lead to electrical discharges between the walls of the void. Ultraviolet light and ozone from these discharges then react with the nearby polymer material, leading to further polymer decomposition and deterioration of the insulation properties.
2. **Water-induced**. In cases where the relative humidity exceeds 70 %, the additives of the polymer matrix can react with water. High voltage cables that are immersed in water or buried are particularly susceptible to this phenomenon.
3. **Chemical**. Channels are formed as a result of contaminants.

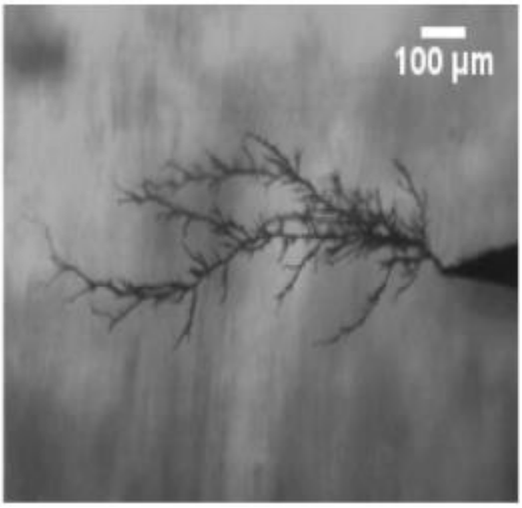

Figure 11: Formation of tree-like channels in PEX cable insulation material [40].

Additives and fillers can affect the formation of tree-like channels. In general, plasticizers reduce the resistance to such channel formation, while fillers have small grains that can act as inert barriers, increasing their resistance. Some stabilizers are added specifically to improve resistance to channel formation. Calcium carbonate ($CaCO_3$) is hygroscopic and can lead to the formation of moisture in the insulating material, which can contribute to water-induced channel formation. Moisture can also stem from the degradation of the alumina trihydrate flame retardant [17].

4.5.2 PEX

Decomposition and charring of PEX will occur only at relatively high temperatures [19]. It has been found that mass loss due to outgassing occurs at temperatures around about 400°C [41], and in general, degradation processes are very slow even near the upper limit of the specified temperature range (usually 90°C conductor temperature for an installation cable). For a PEX insulated cable, the life expectancy will typically be 40 – 60 years at a use temperature of 90°C, and in the temperature range 95 – 105°C the expected lifetime is 7 – 30 years [42]. Studies on polyethylene have shown that added antioxidants can act as an impurity and reduce the dielectric strength. One study suggests that adding 1 % antioxidants resulted in a 16 % reduction in dielectric strength [17]. It has also been observed that PVC can have a negative impact on the properties of PEX. A cable design with PEX conductor insulation and a PVC outer sheath showed more severe thermal degradation of PEX than in the absence of PVC [17].

The formation of tree-like channels, as shown in Figure 11, is a relatively widespread phenomenon for PEX insulated cables used in medium and high voltage installations. Under normal conditions, voltages of several thousand volts would be required to initiate the formation of such channels. For high-quality PEX insulated electrical cables in low voltage electrical installations with an alternating voltage of 230 V, this issue is not significant. One measure mentioned to reduce the formation of three-like channels for PEX insulated high voltage cables is to seal the ends of the cable during transport and storage to prevent moisture from penetrating into the cable.

4.6 Causes of failure or ignition

Many different causes of failure or ignition of electrical cables and installation materials have been reported. Table 3 identifies the most well-known factors that can lead to ignition of PVC insulated electrical cables, caused either by manufacturing defects or incorrect use/installation [5][17].

Table 3: Causes that could lead to failure or ignition of PVC insulated electrical cables [5][17].

Cause	Manufacturing defects	Incorrect use/installation
Errors in the formulation of the insulation material	X	
Extrusion faults for the cable	X	
Contamination	X	
Entrapment of moisture, caused by additives	X	
Overload (currents > 3-7 times the rated capacity)		X
Too much insulation reduces the heat dissipation		X
Heat generation due to damage to the insulation		X
Heat generation due to damage to the conductor		X
Poor connection / contact failure (series fault)	X	X
Dielectric degradation of the insulation material	X	X
Arcing across a carbonized path in the insulation	X	X
Creep of insulation	X	X
Chemical interaction effects	X	X
Voltage surges	X	X

Dielectric degradation of the insulation material and arcing across a carbonized path in the insulation have received relatively high attention as these are quite unique failure mechanisms for PVC insulated electrical cables. Under normal circumstances, PVC has acceptable dielectric properties (cf. Table 2), but the lack of temperature stability means that the insulation properties break down already close to the upper limit of the specified temperature interval (usually up to 70°C conductor temperature for installation cable). Several of the faults listed in Table 3 may result in elevated temperatures. For example, external mechanical stresses can affect the conductor; There may be fractures in the multi-threaded conductor or deformed/reduced conductor cross-section as a result of clamping injuries or too small a bending radius. The consequences of such damage to the conductor may be local heating due to increased current density, which is independent of the cable insulation material used, but for a PVC insulated electrical cable, heating in the conductor will potentially have a major consequence due to the lack of temperature stability for the insulation material.

Dielectric degradation of PVC is a complex phenomenon and was described in the previous chapter. When a breakdown of insulation performance occurs, an arc may propagate through the dielectric medium. Such arcs can have a very high temperature (up to 6000°C) and may cause ignition of nearby combustible material, including the insulation material and surrounding objects. The spontaneous ignition temperature of PVC has been reported to be in the temperature range of 263 – 454°C [19]. Arcing can also cause ablation (i.e. material from the surface of an object is removed by evaporation) without necessarily igniting the material [17]. In such cases, the breakdown will form a permanent and local damage in the insulation, which is referred to as carbonized path.

Carbonized paths are very problematic for PVC insulated electrical cables because these paths can create an electrical connection between the conductors. Laboratory tests have previously been carried out with short-circuit arcs (parallel arcs) in electrical cables and it was found that this type of arcing is repetitive, but in an irregular manner. The following sequence of events was observed [5]:

- There is a flow of current in the carbonized path in the insulation.
- The amperage increases and results in local arcs.
- The arc causes melting of metal and ejection of molten pieces of metal.
- The current strength decreases as a result of the above.
- Continued current flow in the carbonized paths, which in turn causes significantly increased amperage.

It is common to separate the process of formation of carbonized paths in the insulating material into two categories: dry and wet tracking. When moisture is not involved in the process, it is normally a condition that the PVC insulation has been exposed to elevated temperature. In one study, it was shown that carbonized paths can form already after a short time (1 month) heating to 71 - 77°C [43]. Several other studies comparing PVC with other polymer materials concluded that PVC had the worst properties in terms of resisting the formation of carbonized paths in dry conditions [44][45].

Wet tracking can occur when (a film of) water forms a connection between two conductors. An intact cable that is exposed to wet environments (either liquid water or air with high relative humidity) will not normally be affected, but if the insulation material is damaged or weakened (physical and chemical ageing), conditions may be favorable for such tracking. Babrauskas points out that when PVC is tested for tracking in wet environments, the procedure described in the international standard (IEC 60112) is not suitable, as a flat disc/washer, and not an actual cable, is used in the testing [17]. Realistic tests of PVC insulated cables suggest that PVC has poor properties in terms of resisting the formation of carbonized paths in wet conditions. Considerable tracking was observed in all the way down to the voltage range of 50 – 100 V [17][46][47].

HCl's ability to promote corrosion may be an additional factor to the failure resulting from arcing across carbonized paths in PVC insulated cables. The corrosion of the copper conductor forms various reaction products ($Cu(OH)Cl$, $Cu_2(OH)_{3Cl}$) that may actively promote tracking [17].

4.7 Cable classification

The classification of electrical cables in Norway is covered by the European Construction Products Regulation, often called CPR (Construction Products Regulation). CPR was introduced and adopted in 2011 and became mandatory on 1 July 2013. The objective of the CPR was to harmonize the requirements to be set for construction products in Europe, which was not possible with the previous directive called CPD (Construction Products Directive), established in 1989. CPR means that land-based buildings and structures are covered by common regulations that set requirements for safety and fire. It can also be emphasized that the CPR only classifies a product's reaction to fire. This means that the electrical, mechanical, and technical properties of a product will not be covered by the CPR.

Electrical cables are the only electrotechnical product explicitly listed in the CPR, and from 1 July 2017 CPR was introduced for power/installation cables and control/communication cables for permanent and fixed installation (indoors) in Norwegian buildings and constructions. CPR sets requirements for the cable's reaction and impact during a fire, in other words it is not the cable's resistance to fire (functional safe cable) that is covered, only its properties in terms of fire spread, heat generation, and release of substances after a fire has occurred.

Based on these characteristics, cables are classified from class A_{ca} (highest performance, best protection) to F_{ca} (lowest performance) according to Table 4, where "ca" refers to "cable". These are also referred to as euro classes. The extremes here are class A which is non-combustible material and class F which is combustible material with no special requirements for fire properties. An example of a type of cable that satisfies class A_{ca} is a so-called mineral insulated metal sheathed (MIMS) cable where the conductors are insulated with an inorganic powder material (e.g. magnesium oxide) that is encapsulated in a metal pipe. At the opposite end of the classification scale, an unmarked cable of unknown origin will typically be classified in class F_{ca}. For classes B, C, and D, there is also an additional classification indicating criteria for smoke development (s), droplet development (d) and acid development (a) according to Table 4. Here, the higher the performance the lower the number. Class E_{ca} is thus a cable type that only satisfies the criteria for flame spread without additional criteria for heat release, fire spread, as well as smoke, droplet and acid development. E_{ca} in this classification system corresponds to the previous Norwegian minimum requirement given by IEC 60332-1-2. Beyond this, there is no direct correlation between the CPR of 1 July 2017 and previous standards.

The classification system thus allows for 183 different class combinations [4]. Any such combination of main and additional classification can in theory be achieved, but in practice only a few combinations will be fabricated as a given performance parameter can affect and control other performance parameters. PVC insulated electrical cables will satisfy E_{ca}, while electrical cables with halogen-free insulation material will typically satisfy class D_{ca} [4].

The regulation implies that the various players in the market must comply with the CPR requirements, and in practice this entails the following responsibilities:

- The cable manufacturer must issue a performance declaration (DoP), perform CE marking and 3rd party certification according to the CPR.
- The importer must ensure cables are CPR compliant.
- The wholesaler must ensure that products they carry are tested and labelled according to the CPR.
- The responsible designers must ensure that cables are CPR compliant.
- The installer must acquire and apply the correct product/documentation.

Table 4: Classification of electrical cables according to the Construction Products Regulation (CPR) and associated test methods.

Class	Criteria	Test method	Additional classification	Test methods
Aca	Calorific value	EN ISO 1716	-	
$B1_{ca}$	Heat dissipation Fire spread Flame spread	30 kW flame source EN 60332-1-2	S1A, S1B, S1, S2, S3 D0, D1, D2 A1, A2, A3	EN 61034-2 / 50399 EN 50399 EN 60754-2
$B2_{ca}$	Heat dissipation Fire spread Fire Development Index Flame spread	20.5 kW flame source EN 60332-1-2	S1A, S1B, S1, S2, S3 D0, D1, D2 A1, A2, A3	EN 61034-2 / 50399 EN 50399 EN 60754-2
C_{ca}	Heat dissipation Fire spread Fire Development Index Flame spread	20.5 kW flame source EN 60332-1-2	S1A, S1B, S1, S2, S3 D0, D1, D2 A1, A2, A3	EN 61034-2 / 50399 EN 50399 EN 60754-2
D_{ca}	Heat dissipation Fire Development Index Flame spread	20.5 kW flame source EN 60332-1-2	S1A, S1B, S1, S2, S3 D0, D1, D2 A1, A2, A3	EN 61034-2 / 50399 EN 50399 EN 60754-2
E_{ca}	Flame spread	EN 60332-1-2	-	
F_{ca}	Does not satisfy class E_{ca}		-	

4.8 Standards for cable testing

In Norway, committee NK20 (Electric cables) in the Norwegian Electrotechnical Committee (NEK) develops and monitors standards that describe requirements for construction, materials and test methods related to power and signal cables. The committee is also working on European standards

(EN) in connection with the CPR/Construction Products Regulation on fire requirements for cables in Europe. The most relevant European standards for testing electrical cables are:

- **EN 50575:2014**: Power, control and communication cables - Cables for general applications in construction works subject to reaction to fire requirements.
- **NS-EN 13501-6:2022**: Fire classification of construction products and building elements - Part 6: Classification using data from reaction to fire tests on power, control and communication cables.
- **EN 50576:2022**: Electric cables - Extended application of test results for reaction to fire
- **NEK EN 50399:2022**: Common test methods for cables under fire conditions - Heat release and smoke production measurement on cables during flame spread test - Test apparatus, procedures, results.
- **EN 60332-1-2:2004**: Tests on electric and optical fiber cables under fire conditions Part 1-2: Test for vertical flame propagation for a single insulated wire or cable - Procedure for 1 kW pre-mixed flame.
- **NEK EN 61034-2:2005**: Measurement of smoke density of cables under defined conditions - Part 2: Test procedure and requirements.
- **NEK EN ISO 1716:2018**: Reaction to fire tests for products — Determination of the gross heat of combustion (calorific value).
- **EN 60754-2:2014**: Test on gases evolved during combustion of materials from cables - Part 2: Determination of acidity (by pH measurement) and conductivity.

5 Considerations

In this chapter, the themes presented in the previous chapters will be discussed and put into context. Some relevant questions that have been investigated are:

- Who sets the requirements for cable insulation materials? Where are these requirements stated and how did they get defined?
- To what extent are PVC and PEX used in Norway and in Europe?
- How many fires are there in real terms annually in Norway that are caused by series faults in electrical installations? What are the costs for the society?
- Can the use of PEX insulation interrupt or slow down the course of a series fault?
- Can using PEX instead of PVC as a cable insulation material be an effective fire prevention measure?

5.1 Requirements for installation cables in Norway

It is up to each European country to define its fire safety level under the CPR. This will vary depending on the building traditions and building rules of the country, and in general, the local fire hazard situation. The final decision on the minimum level of fire performance lies with the national authorities, which in Norway are DSB and the Norwegian Building Authority (DiBK). In Norway, fire safety requirements for electrical cables are specified in the following regulations, with associated years:

- Regulations for buildings
  - Construction Products Regulation (CPR) - 2013
  - Regulations on technical requirements for construction works (TEK17) - 2017
- Regulations for electrical installations
  - Regulations on low voltage electrical installations (FEL) - 1999
  - Electrical low voltage installations (NEK 400:2022) – 2022
- Regulations for electrical equipment
  - Low Voltage Directive (2014/35/EU) - 2014

The following will provide an overview of relevant sections related to fire technical requirements for electrical cables in TEK17 and NEK 400:2022.

5.1.1 TEK17

The regulations relating to technical requirements for construction works (TEK17) define the minimum of characteristics a construction work must have in order to be constructed legally in Norway. The last edition entered into force on 1 July 2017 and replaced from the same date TEK10. TEK17 is a so-called function-based regulation that does not stipulate detailed requirements for individual products, but requirements regarding which functions the various products must satisfy, such as safety in the event of fire [24]. The minimum performance that the products must fulfil in order to satisfy the regulatory requirements is specified in the guidelines to the regulations. The services are specified in relation to the consequences a fire can have for different construction works, based on the construction works' **Fire class** and **Risk class** [24]. TEK17 defines 6 different **Risk classes** for a construction works, or for different uses in a construction works, based on assessments of the danger a fire may pose to life and health, where risk class 6 has the highest requirements for fire protection measures. Risk class 6 includes hospitals and accommodation, while homes and offices are placed in risk classes 4 and 2 respectively. There are also 4 different **Fire classes** for a building based on the consequences a fire may have for damage to life, health, social interests and the environment, where fire class 4 applies to buildings where the consequence is considered to be particularly great. The fire classes shall form the basis for the design to ensure the load-bearing capacity of the building in the event of fire, while the risk classes shall be used as a basis for the design of the building to ensure safe escape and rescue in the event of a fire.

The requirements that apply to cables, wiring systems and encapsulations in electrical installations in construction works are given in § 11.9 (*Properties of materials and products in the event of fire*) and § 11.10 (*Technical installations*) in TEK17. §11.9 states the following:

1) *Construction works must be designed and executed in such a way that there is low likelihood of fire occurring, developing, and spreading. Consideration shall be given to the use of the construction works and the time required for escape and rescue.*
2) *Materials and products must have properties that do not make an unacceptable contribution to the development of fire. Emphasis should be placed on the possibility of ignition, the rate of heat release, smoke production, the development of burning droplets and time to flashover.*

§11.10 states the following:

1) *Technical installations shall be designed and executed in such a way that the installation does not significantly increase the risk of fire occurring or of fire and smoke spreading.*
2) *Installations that are assumed to have a function during fire shall be designed and executed in such a way that their function is maintained for the time necessary. This also includes the supply of water, power or signals necessary to maintain the operation of the installation.*

The guide to §11.10, first paragraph, states the following about what is related to electrical installations:

- *Classes for different applications for cables are specified in NEK 400. For installations for electronic communications apply NEK 702 (Information technology – Installation). This refers to NEK 400.*
- *Pre-accepted performance*
    1) *Cables must not be laid over suspended ceilings or in cavities in an escape route unless one of the following points is met:*
        a) *The cables represent low fire energy, i.e. less than approx. 50 MJ/running meter of cavity*
        b) *The cables are routed in a separate shaft with shaft walls that have fire resistance corresponding to the fire cell limiting building part*
        c) *The ceiling has fire resistance corresponding to the fire cell limiting building part*
        d) *The cavity is sprinkled.*
    2) *Cables that constitute little fire energy, i.e. less than approx. 50 MJ/running meter corridor or cavity, can be routed unprotected through the escape route. This is a specific exception that applies to cables and cannot be used as justification for other deviations from pre-accepted performance.*

5.1.2 NEK 400:2022

NEK 400:2022 [48] is a collection of 43 norms within low voltage electrical installations and has been prepared by committee NK64 (*Low voltage installations*) in the Norwegian Electrotechnical Committee (NEK). The current version came into effect on 1st of October July 2022 and from the same date replaced corresponding parts of NEK 400:2018. NEK 400:2022 is a Norwegian adapted version of the IEC 60364 series and the CENELEC HD 60364 series. NEK 400:2022 states the following:

- *NEK 400:2022 specifies requirements for design, execution, and verification of low voltage electrical installations. The requirements are intended:*

- *to safeguard people (persons), livestock and property against hazards and damage that may arise from the intended use of low voltage electrical installations, and*
- *to ensure that these installations function as intended, and*
- *to help ensure that installations do not cause unacceptable inconveniences.*

Provisions relevant to the fire properties of electrical cables are mainly collected in NEK 400-4:2022 and NEK 400-5:2022:

- The substandard NEK 400-4 contains the basic requirements for protection, including functional requirements for protection against thermal effects, specified in NEK 400-4-42.
- The sub-standard NEK 400-5 includes requirements for the selection and installation of electrical equipment that must be satisfied in order to fulfil the functional requirements given in NEK 400-4.

In NEK 400-4:2022, the following formulations are relevant for electrical cables, where classification of external influences is described in Table 5 below:

- *428.1: Areas classified with external influences <u>BD2, BD3 or BD4</u> for **emergency evacuation conditions***
  - *428.1.1.7: Cables shall at least satisfy the requirements of class* $\mathbf{D_{ca}}$***-s2d2a2*** *defined in NS-EN 13501-6. If the cables are protected by an automatic fire suppression system, such as a fire sprinkler system, cables that satisfy the class* $\mathbf{E_{ca}}$ *defined in EN 13501-6 may be used.*
  - *428.1.1.8: Wiring systems shall not contribute to the spread of fire.*
  - *428.1.2.5: Cables and wires, if not protected by an automatic fire suppression system (such as a fire sprinkler system), shall not represent a fire energy exceeding 50 MJ per running meter escape route.*
    - *Guidance: This requirement is not part of the certified scheme for fire requirements for cables under the Construction Products Regulation (CPR).*
- *428.2: Areas classified as external influences <u>BE2 or BE3</u> for properties of materials processed or stored*
  - *428.2.7: Equipment shall, as a minimum, be selected in accordance with the following requirements:*
    - *Cables shall at least satisfy the requirements of class* $\mathbf{E_{ca}}$ *defined in EN 13501-6*
    - *Where the risk of flame spread is high, for example in long vertical shafts or bundled cables, it is recommended to use cables that at least satisfy the requirements of class* $\mathbf{D_{ca}}$***-s2d2a2*** *defined in NS-EN 13501-6.*

In NEK 400-5:2022, the following formulations are relevant for electrical cables:

- *527.1: Precautions within building fire cell*
  - *527.1.3: Cables shall at least satisfy the requirements of class* $\mathbf{E_{ca}}$ *defined in NS EN 13501-6 and equipment classified as flame retardant according to section 527.1.6 and equipment classified as flame retardant can be installed without special precautions.*
  - *Cables that do not satisfy the class* $\mathbf{E_{ca}}$ *requirement defined in NS EN 13501-6 shall, if used, be limited to short lengths for connecting equipment to the fixed installation and shall never be routed from one fire cell to another. In installations where there is a special risk, cables that at least satisfy class* $\mathbf{D_{ca}}$***-s2d2a2*** *defined in NS EN 13501-6 may be necessary.*
- *560.8: Wiring systems*
  - *560.8.1: One or more of the following wiring systems shall be provided for emergency power systems to operate during a fire:*
    - *mineral insulated cables in accordance with EN 60702-1 and EN 60702-2, or*

- *functionally safe cables in accordance with relevant parts of the NEK IEC 60331 series and which at least satisfy the requirements of class* ***D_{ca}-s2d2a2*** *defined in NS-EN 13501-6, or*
- *a wiring system that maintains the necessary protection against fire and mechanical damage.*

Table 5: Classification of external influences defined in Table 51A of NEK 400:2022.

Code	External influence	Necessary features of the selection and assembly of equipment
BD	*Evacuation conditions in emergency situations*	
BD1	Low density of persons / easy escapes	Low population density and easy escape.
BD2	Low density of persons / difficult escapes	Low population density and difficult escape. Tall buildings.
BD3	High density of people / easy escapes	High density of people and easy escape. Areas open to the general public (theaters, cinemas, shopping malls etc.).
BD4	High density of persons / difficult escapes	High population density and difficult escape. Tall buildings available to the general public (hotels, hospitals etc.).
Code	**External influence**	**Necessary features of the selection and assembly of equipment**
BE	*Properties of materials processed or stored*	
BE1	No significant risk	Normal.
BE2	Fire hazard	Manufacturing, processing or storage of combustible materials including dust. Barn, woodworking company, paper mill, etc. Equipment made of materials with fire resistance. Arrangement to avoid that temperature rise or sparks in electrical equipment may lead to ignition of fire in the surroundings.
BE3	Risk of explosion	Processing or storage of explosive substances, or substances with low flash points, including gas and dust and explosives. See NEK 420. Oil refineries, hydrocarbon storages, food industry, etc. Requirements for equipment for use in hazardous areas.
BE4	Pollution hazard	Presence of unprotected foods, pharmaceutical products and similar products without protection. Food industry, kitchen. Measures may be necessary to prevent food etc. from being contaminated by electrical equipment, for example by a broken lamp, in a faulty situation. Appropriate measures such as: • protection against fallout of parts from lamps and other easily breakable equipment, or • shielding against harmful radiation in the IR and UV range.

SINTEF Report NBL A12123 "*Electrical cables and fire risk – Fire properties of cables, wiring systems and encapsulations*" is relevant to the current cable classification in Norway. The work was carried out in 2012 under the research agreement between SINTEF NBL and DSB and was partly financed by DiBK. The overall objective of the report was "*to clarify, define and specify the fire properties and performance of cables, wiring systems and distribution encapsulations based on regulations for* *electrical installations (FEL and NEK 400) and regulations for buildings (TEK10)*" [24]. Chapter 4 of the report provides the following summary of the fire requirements for electrical cables at the time [24]:

- *"There is no requirement for fire properties of cables to be documented by testing in the current building regulations, and pre-accepted solutions based on the euro classes are not yet specified in the guidelines. Fire resistance performance is also not indicated in terms of classes".*
- *"NEK 400 is accepted as a method description to satisfy the safety requirements stipulated in FEL. The performance stated in comments must be regarded as recommendations rather than requirements. This applies to several of the references to fire safety methods in NEK 400 chapters 400-4 and 400-5".*
- *"However, some references to fire technical test methods are given in the text itself and must therefore be regarded as requirements that must be followed if an electrical installation is to be performed in accordance with NEK 400. These references are provided under section 422.1 on fire resistance of wiring systems that supply emergency power circuits, and under 422.3.4 on cables and wiring systems".*
- *"NEK 400 thus includes a set of fire safety requirements for different parts of low voltage electrical installations in Norwegian construction works. However, these requirements are not completely unambiguous when reference is made to requirements and criteria in the building regulations. The use of area categories BD2, BD3 and BD4 in the electricity regulations and the use of risk classes and fire classes in the building regulations is an example of different concepts that can create unnecessary problems during design".*

Chapter 5 of the report assesses new fire requirements for electrical cables in construction works. Some relevant statements are as follows [24]:

- *"In order to arrive at a robust proposal for how the new classes for fire impact properties can be implemented in the guidelines to building regulations, it is necessary to have a better basis for decision-making than we have access to today. Such a basis could, for example, be developed through a Nordic collaborative project, which includes a risk analysis of the products, and where experiences are exchanged, and joint assessments made".*
- *"A main principle should be that the properties of cables in the event of fire are regulated in the same way as other construction products. In areas where there are strict requirements for surface materials on walls and ceilings, strict requirements should also be imposed on the fire properties of electrical cables. The requirements can also be assessed on the basis of the quantity and location of the cables. In areas with particularly strict requirements for fire safety, such as escape routes, an alternative solution may be to build in or cover the cables, so that they will not participate significantly in an early phase of fire development. In addition, the cables must be regulated with regard to the possibility of ignition due to electrical failure. This is largely taken care of in today's electricity regulations".*
- *"As an example, proposals have been given for how fire requirements for products in escape routes should be regulated. However, a final proposal for how the new fire classes can be incorporated into the guidelines for building regulations should be coordinated with the other Nordic countries. This report will form a good basis for further Nordic co-operation".*

As a continuation of this work, the SINTEF report NBL A13111 "*Conditions for Nordic harmonisation of fire classification of cables - Proposal of implementation of the new European classification system in the building regulations*" was published in 2013. The report was prepared for the building authorities in Denmark, Sweden and Norway in cooperation with the fire laboratories in all three countries. The main objective of the work was to propose how the new European system for classification of the reaction to fire for electrical cables can be implemented in the Nordic building regulations. Based on a review of fire requirements at the time, fire statistics and experiences from fires where electrical cables had been involved, the following recommendations were given, together with the summary in Table 6 [4]:

- *"All electric cables in buildings shall at least fulfill class E_{ca}".*
- *"For spaces equipped with a fire alarm or an automatic fire suppression system, a cable class of one step lower than the required class may be used, i.e. E_{ca} instead of D_{ca} – s2d2, or D_{ca} – s2d2 instead of C_{ca} – s1d1".*
- *"For the subclassification of smoke acidity, the proposal has no requirements for requirements since there currently are no such requirements for other construction products. It should however be noted that for purchasers wishing to require cables that only produce acid free smoke there is the possibility of adding an a1 or a2 requirement. This may be the case in areas where protection of electronic equipment, data servers etc against corrosion by smoke is an essential requirement".*

Table 6: Recommendations for requirements for electrical cables submitted to the Nordic authorities in 2013 [4].

Exposed area of cable surface	General requirement	1 and 2 story individual dwelling houses	Escape routes for all occupants
> X %*	D_{ca} – s2d2	E_{ca}	C_{ca} – s1d1 **
< X %*			D_{ca} – s2d2

* The percentage X should be set in the range of 2 – 10 % and be calculated as the exposed area of cables in relation to the area of the ceiling.
** This requirement applies only to the part of exposed area that exceeds X %.

The report specifies that cables with PVC insulation will satisfy the requirements of class E_{ca}, while cables without halogen in the insulation will satisfy class D_{ca}, according to information from Norwegian cable manufacturers.

The discussion section of the report the following is stated [4]:

- *"The principle for determining reaction to fire requirements for cables should as far as possible follow the same logic as the requirements set to other types of building materials. That means that the requirements in certain areas where the risk for life and health is high in case of fire (e.g. escape routes, institutions, hotels etc) will be higher than in areas with a lower risk level".*
- *"Available fire statistics indicate that a small number of building fires start in cables, the share may be in the range of 1- 2 % of all building fires. However, the statistical data is very sparse, and contains a large degree of uncertainty. The most thorough analysis of building fires with electrical cause in the Nordic countries was a study of Norwegian fire statistics, but the statistical data is not detailed enough to give a good status of how cables contribute by fire start and fire development".*
- *"The reports from fires where cables were involved show that more of these fires led to large economical and practical consequences beyond the fire damage, because important functions like power distribution and data communication were affected. Considerable smoke production is also a common factor for these fires".*
- *"This project has shown that there is very little information available on how electric cables in buildings contribute to fire safety. This is the case internationally, but also especially for the Nordic countries. It would therefore be useful if information about cables in fires was collected in the national fire statistics. However, we believe that this could be difficult to carry out, and that the uncertainty related to the collected information would be large".*

The formulations in NEK 400:2022 largely coincide with the recommendations given to the Nordic building authorities (cf. Table 6) in the SINTEF report NBL A13111 in 2013. These recommendations were based solely on the fire properties of the product, that is, the reaction of the cable to fire after a fire had occurred. The thermal degradation of the insulating ability of PVC was not taken into account when drawing up the recommendations. Both the main author of the SINTEF report and the representative of the client (DiBK) have been contacted and both have been able to confirm this. Given the problems associated with thermal decomposition and the formation of carbonized paths in PVC, there is much to suggest that the electrical safety aspect should also be taken into account when defining the fire requirements for electrical cables.

Current CPR requirements for electrical cables in the Nordic countries, Germany, England, and France are presented in Table 7. This table indicates that the requirements in Norway do not differ significantly from those in other European countries. It is worth noting that the recommendation in Norway is D_{ca} – s2d2a2 for all applications, which in practice means halogen-free insulation material. Furthermore, it can be noted that the classification E_{ca} satisfies the minimum requirements in all these countries, which in practice means that there are applications where it is permissible to use PVC-insulated electrical cables.

Table 7: Overview of CPR requirements for electrical cables in the Nordic countries and selected European countries. The information is taken from EuropaCable's website.

Country	Minimum requirement	Recommendation	Area of use
Norway*	E_{ca} D_{ca} - s2d2a2	D_{ca} - s2d2a2	E_{ca} for all applications D_{ca} - s2d2a2 where low smoke and acid development product is required
Sweden*	E_{ca} D_{ca} - s2d2 C_{ca} - s1d1		E_{ca} for buildings < 200^{m2} and warehouse/industrial buildings < 500 m2 D_{ca} - s2d2 for other buildings C_{ca} - s1d1 for escape routes
Denmark	E_{ca} E_{ca} - d2		E_{ca} for electrical and signal cables in accordance with DS/EN 13501-6 E_{ca} - d2 for pipes in accordance with DS/EN 13501-1
Finland	E_{ca} D_{ca} - s2d2a2 C_{ca} - s1d1a2		E_{ca} Indoor Minimum Requirements D_{ca} - s2d2a2 for public buildings C_{ca} - s1d1a2 for escape routes and healthcare facilities
Germany	E_{ca} C_{ca} $B2_{ca}$		E_{ca} for buildings, height < 13 meters, area < 400 m^2 C_{ca} for other types of buildings outside the escape route $B2_{ca}$ for escape routes
England	E_{ca} D_{ca} - s2d2a1 C_{ca} - s1d2a1		E_{ca} for low-risk installations D_{ca} - s2d2a1 for cable in installations with increased requirements C_{ca} - s1d2a1 for power cable in installations with increased requirements
France	E_{ca} C_{ca} - s1d1a1 $B2_{ca}$ - s1aa1		E_{ca} for installations without specific requirements C_{ca} - s1d1a1 for residential buildings $B2_{ca}$ - s1aa1 for tunnels for public transport

* If the cables are protected by an automatic fire suppression system, cables that satisfy a class lower class can be used.

5.2 Use of PVC insulated installation cable

NEK 400 specifies in Chapter 523 (Current-carrying capacity) that electrical cables in a low voltage electrical installation have a limitation which means that the current to be carried in a conductor for long periods during normal operation shall not exceed the temperature limits specified in Table 52A, which specifies the maximum operating temperature for different types of insulation [48]. For PVC insulated electrical cables, this temperature limit is set at 70°C. The corresponding limit for PEX and ethylene propylene rubber-insulated electrical cables is set at 90°C. Table 52A specifies that when a conductor operates at a temperature exceeding 70°C should ensure that the equipment to which the conductor is connected is adapted to the resulting temperature created in the terminals. It can be added here that many Norwegian houses and buildings are built of wood with a lot of (thermal) insulation. When electric cables are placed inside an insulated wall, improper installation combined with high current loads may entail a risk that the conductor temperature exceeds 70°C due to reduced heat dissipation to the environment, cf. Table 3.

NEK 400 states that the maximum permissible conductor temperature given in Table 52A is taken from NEK IEC 60502. The latest edition of this standard is from 2021 and is titled "*Power cables with extruded insulation and their accessories for rated voltages from 1 kV (U_m = 1.2 kV) up to 30 kV (U_m = 36 kV)*". It has previously been pointed out that the standards applicable to the use of PVC insulated electrical cables are based on research conducted on PVC in the 1950s. The SINTEF report NBL A06121 states the following related to this [5]:

- *"Both UL and IEC standards group electrical insulation materials into temperature classes on the basis of 50-year-old research results [49]. These tests have proven that PVC can be classified or approved for use up to 105°C".*
- *"Stricker 1974 [43] found that significant amounts of the plasticizer disappeared at 71 - 77°C during a month's exposure to 20 - 50-year-old heating cables. It was concluded that none of the cables, which were rated for 90 or 105°C, should be used at temperatures above 70°C".*
- *"The fact that glowing connections are a very relevant cause of fires in the EU and the USA is also reflected in the standards for approval of plastic materials used in electrical materials and equipment, namely the standards IEC60695 and UL94*
    - *These standards simulate a glowing metal wire, with temperatures in the range of 500 - 900°C, which should touch the plastic material for a certain period. If the material does not ignite or self-extinguish within a certain period, it is approved.*
    - *It is pointed out that arcs can be more intense than glowing connections, and that the standard thus does not capture arcs as a source of ignition".*

This suggests that the problem of thermal degradation of the dielectric properties of PVC insulation is well known and taken into account when these temperature limits in Table 52A have been determined, although research on PVC was done in the 1950s that apparently overestimated the thermal properties of the insulation material.

Thus, the CPR requirement for electrical cables in Norway specifies that D_{ca}–s2d2a2 is recommended for all applications. However, it is perceived that PVC insulated electrical cables are used extensively in Norway, which has been confirmed by various players in the electricity industry, representatives from DiBK and several norm committee chairs in NEK. The reasoning for this is not clear, but it has been pointed out that the mechanical properties of PVC make it easy and predictable to handle/install and that both installation practices and work procedures are well-established and almost to be regarded as an established habit. If you switch to another product, e.g. a cable with PEX insulation, it may require changing procedures, which may result in an increased cost and possibly increased risk in the form of solutions that are not well proven being adopted. In this context, it has been suggested that there is a considerable pressure on prices in the building industry and that there is to some extent a form of aversion to measures that may add costs.

Through conversations with players in the electricity industry, it has emerged that the use of cables that satisfy class D_{ca} is relatively widespread in Sweden, although the regulations allow for the use of cables that satisfy class E_{ca} in buildings under a given area, while in Denmark halogen-free cables are widely used in E_{ca} class, without the insulation material necessarily being PEX. It may appear that environmental considerations play a not insignificant role here, as halogen-free products are often presented (in marketing) as "environmentally sound", which can be crucial for environmentally conscious customers. It is unclear whether electrical safety considerations also play a role. Based on this, it can be questioned whether environmental awareness is less widespread in Norway compared to Sweden and Denmark. In an article written by the chairman of the board of the Forum for the flooring industry in connection with the choice of PVC flooring for the new Stavanger University Hospital, it is emphasized that "*the Stockholm region has decided to phase out products containing PVC and decided that the use of flooring materials that include PVC must be reported for non-conformity in projects. The real estate company Locum, which builds, owns, and manages the region's hospital and healthcare facilities, recommends using other alternatives where possible*" [50].

The environmental aspects of PVC use are therefore worth commenting on. Chlorine is a strong oxidant, meaning it readily reacts with organic molecules to produce a variety of chlorinated compounds. Many of these chemicals accumulate in the ecosystem, including fish, wildlife, and humans, and are toxic at relatively low doses [51]. Although PVC is thermoplastic and therefore potentially suitable for recycling, the totality of added stabilizers, plasticizers, and other hazardous substances (including phthalates) during production plays a role in the material's suitability for end-of-life recycling. For successful recycling, PVC products must be "super-separated" by product type to prevent them from going to incineration or landfill [51]. Furthermore, a recent study related to comparative data analysis of the total energy consumption of three types of polymer materials (PVC, polyethylene and polypropylene) showed that PVC has a higher energy consumption and greenhouse gas emissions compared to the other two polymer types [52].

Of all industrial applications, PVC production is the largest chlorine consumer, with an estimated 30 % of elemental chlorine going to PVC [51]. In general, PVC plastic is widely used in buildings in Norway. In a report from 2023 prepared by Mepex Consult AS and Multiconsult AS, the following is written about the use of PVC in buildings [32]:

- *"A commercial building being designed in Drammen (K33, Kreftingsgate 33) has 198 tons of plastic products, of which 13 % is PVC plastic".*
- *"PVC is used, among other things, for conduit pipes for electrical infrastructure, pipes for cold water intakes, windows and profiles, gutters, roof and floor coverings, carpets. For drainage pipes, the use of PVC has been phased out (since the 90s) as the material tended to expand and become brittle by heat exposure".*
- *"Due to previous use of environmentally harmful additives, some plastics have subsequently been defined as hazardous to health and the environment when refurbishing buildings. Because plastic in building and construction has a long lifetime, there are still plastics with substances hazardous to health and the environment in today's buildings".*

The use of PVC plastic has long been controversial, and several non-governmental organizations (NGOs) are actively working to phase out PVC use in Europe, including Health Care Without Harm (HCWH) Europe, Zero Waste Europe and the Health and Environment Alliance (HEAL). The aim of these organizations is to get the EU to develop a plan for the full phase-out of PVC by 2030. A report published by the European Commission in 2022 examines the use of PVC in the context of a non-toxic environment [53]. This report presents the following related to electrical cables [53]:

- *"The market share of PVC used for the production of electrical cables has decreased in the EU from 11 % in 2004 to 7 % in 2017".*
- *"In recent years, cable recycling has become less attractive because prices have been negative, i.e. recycling operators have had to pay to treat them. Due to restrictions from the Chinese government on imports of certain types of plastic in 2019, there is currently an abundance of cable waste on the market. Mainly cable sheathing, which are a side product of cable recycling*

and made from PVC, occurs in large quantities. Due to the abundance, the prices of cable sheathing in 2019 became negative (-200 to -50 €/ton)".

- *"In electronics, alternative cable coatings and jackets are available that are technically feasible, although it is recognized that specific requirements differ. The environmental and health risk reduction is less clear - all alternatives are plastics, some of which pose similar concerns to PVC, but which are the subject of potential regulatory action. Costs of alternatives differ".*

This last point is a summary of an analysis of alternatives to PVC based on their technical and economic feasibility, capacity to reduce overall risks and their availability. This analysis is presented in Tables 7-36 in the report and is reproduced here in Table 8 for electrical cables. Here, the background colors green, yellow and red in the table represent low, medium and high risk, respectively. The table shows that some of the material alternatives included in this analysis contain harmful substances, including chlorinated polyethylene (CPE), fluorinated ethylene propylene (FEP), ethylene tetrafluoroethene (ETFE), polytetrafluoroethene (PTFE), perfluoroalkoxy (PFA), and chloroprene (CP), all of which contain the halogens chlorine or fluorine. This means that the category "Comparable hazard and risk" is rated red. The analysis suggests that there are minor challenges related to technical feasibility and accessibility, while there are certain challenges related to economic feasibility and access to reliable information.

Table 8: Analysis of alternatives to PVC cable insulation material [53].

Options considered	Technically feasible	Economically feasible	Comparable hazards and risks	Accessibility	Uncertainty and quality of information
PE, CPE, PP, PUR, TPE, mPPE, FEP, ETFE, PTFE, PFA, PEX, CP, EPDM, EVA, silicone rubber	Plastic or synthetic rubber alternatives are available and in use, but each performs differently.	Material costs vary; some are comparable whilst others are significantly more expensive. Costs for articles reflect this, although the differences are likely to be lower.	Some alternatives are fluoropolymers and may be affected by ongoing regulatory action, others contain harmful substances posing recycling challenges. Additives still likely to be required in several cases.	Alternatives widely available. Increases in production and/or import volumes may be necessary.	Lack of reliable economic and cost information on every alternative and it is recognized that specific performance requirements differ significantly within the sector.

One of the objections to the total phasing out of PVC has been that there are products containing PVC on the market that do not have full-fledged substitutes. In the healthcare sector, medical grade PVC has been shown to have a number of beneficial properties, including biocompatibility, sterilizing ability, flexibility, transparency, material strength, and low cost, as well as being proven over many decades. In medical technology, therefore, criticism has largely been directed at the release of plasticizers in the PVC material, especially the phthalates di-2-ethylhexyl and dioctyl, which exhibit reproductive toxic properties. Phthalate-free plasticizers have therefore been developed to significantly reduce the risk. Active efforts are being made in this industry to find good substitute materials for medical-grade PVC. For electrical cables for low voltage electrical installations, there will typically be no similar objections for the replacement of PVC-based insulation material. From a cable manufacturer that has been contacted in this project, it has been stated that substitute materials exist to a large extent and that for this type of cable (for installation in low voltage systems) it is quite possible to replace PVC both as insulation material and outer sheath. However, as indicated in Table 8, there are special applications, for example in electronics, where the substitute materials will bring with them a hazard and risk comparable to PVC.

When it comes to the cost of a PVC insulated electrical cable compared to an equivalent PEX insulated electrical cable, it appears that neither the production cost nor the selling price are significantly different [53]. In dialogue with a cable manufacturer, it has been stated that the price of an electric cable will generally depend on production volume and demand, as well as the material cost itself, of which the metal in the conductor is the largest cost driver. The price will also be affected by energy consumption, material consumption, line speeds, and batch size. A comparison of two relatively similar cables (similar conductor cross-section, both with PVC outer sheaths) from this manufacturer shows that the cable with PEX insulated conductors comes out favorably in terms of price compared to the variant with PVC-insulated conductors. The simplified explanation for this is that the cable with PEX insulation has a slimmer design, i.e. less use of plastic drives the cost down. A similar comparison between a PFSP cable (E_{ca}-rated) and an IFSI cable (halogen-free, D_{ca}-rated) shows that the cost price will be relatively equal. In some cases, an IFSI cable may be less expensive than a PFSP cable, but more often than not, it will be slightly more expensive. Traditionally, PFSP cables have been more widely available in Norway.

Finally, Table 9 presents a comparison of relevant properties of electrical cables with selected insulation materials [53]. It appears from the table that PVC and PEX have comparable characteristics in all the considered categories. Taking into account thermal stability and the environmental aspect, it appears that PEX outcompetes PVC as a cable insulation material.

Table 9: Comparison of properties of electrical cables with different insulation materials [53].

Insulation material	Temperature application range (°C)	Dielectric strength (kV/mm)	Fire-resistance	Chemical resistance	Flexibility	Durability	Cost (€/m)*
PVC	-20 – 105	25	Good	Good	Good	Good	0.4 – 1.7
PEX	-40 – 105	50	Good	Good	Good	Good	0.4 – 1.3
Polyethylene	-60 – 80	25	Bad	Bad	Good	Good	0.84
Polypropylene	-40 – 105	20	Bad	Good	Good	Useful	-
Polyurethane	-55 – 80	20	Bad	Good	Good	Good	-
PTFE	-60 – 200	20	Good	Good	Good	Good	1.3 – 3.4
EPDM	-55 – 125	25	Bad	Bad	Good	Good	1.25
Silicone rubber	-80 – 180	20	Good	Useful	Good	Useful	1.1 – 3.0

* Retail price for 1 meter 0.75 mm^2 (18 AWG) cable.

5.3 Course of a series fault for a PVC insulated electrical cable

Under normal circumstances, a PVC insulated electrical cable will work well and have a long lifetime in a low voltage electrical installation. However, if such a cable is exposed to heat, the risk of the insulation material failing increases, which can result in a dangerous situation. As pointed out in the introduction to Chapter 3, a series fault (contact failure) can lead to dissipation of electrical energy with subsequent heat generation and local heating (also called resistance heating). For a PVC insulated electrical cable, thermal decomposition and the formation of carbonized paths may occur at relatively low temperatures, i.e., far lower temperatures than the point of ignition of both the insulation material and a surrounding combustible material. For example, in a cable design with several live conductors, creep currents in carbonized paths can facilitate the formation of stable (continuous) arcs in the insulation material between the conductors. In an NTNU master's thesis on series fault protection, the following statements were presented for this type of arcing [6]:

- *"An arc through a carbonized pathway between two cables provides a more realistic failure situation than the arc generator. It represents the type of series arc considered by Martel to be the most damaging [2]".*
- *"Shea showed that a series arc over a carbonized pathway can start a fire at currents as low as 1.7 A_{rms} [29]. Shea also points out that it is probably possible to start a fire at even lower currents, but this was not proven."*.

In his doctoral thesis, Martel presents the following findings for stable arcs in carbonized paths [2]:

- *"The thermal properties of an insulation material have a significant influence on the initiation of stable series arcs. One reason that was often mentioned is the charring of the polymer that results in a conductive track and supports the restrike of the arc after each current zero-crossing".*
- *"PVC-based polymers have a high probability of ignition that is directly related to the initiation of a stable arc. The amount of energy needed to obtain a stable arc is in the range of 10 J to 1000 J".*
- *"The PE-based polymers do not ignite because it is not possible in these conditions to initiate a stable arc. For a few additional tests, the duration was extended to 5 minutes instead of 200 s. No stable arc and no ignition could be observed".*
- *"The evidence from the investigations shows a clear relationship between the decomposition of the polymers into char and the initiation of stable series arcs that can lead to the ignition of the insulating material. It was observed that aliphatic polymers like PE and other halogen-free polymers may not easily char. In contrast, PVC is known to undergo arc tracking and charring. All the tested polymers could burn, but only the PVC and the PP-based polymers were able to produce a carbonized track under the thermal stress provoked by electrical faults and anomalies such as glowing connections and contact arcing. This carbonized track can initiate a very stable arc (of the type arc due to creepage on char) that has a higher power density than other faults and can quickly ignite the flammable materials. In contrast, the PE-based polymers and in general the halogen-free polymers do not easily carbonize and seem to be very "arcing-resistant".*
- *"The non-contact series arcing that is due to creepage on char could be identified as the most hazardous form of series arcing: it can be the result of many other phenomena like glowing and contact arcing, become self-sustained, and dissipate a significant amount of heat. The other types of arcing do not have the same capability to sustain themselves and dissipate a lot of heat".*
- *"Series contact arcing dissipates much less power than series arcing due to creepage on*
- *char because it is less stable and the arc voltage is lower."*

Very few studies have been published in which the resistance of PVC and PEX insulated electrical cables to a series fault has been systematically tested. In his doctoral thesis, Martel has analyzed resistance to series arcing and glowing connections for PVC and PEX insulated electrical cables, and the main findings are summarized in Table 10 [2]. It is reported that the PEX insulated cable performs significantly better than the PVC insulated cable in all categories. Low mass loss is synonymous with a low degree of thermal decomposition, while large ash production during combustion means good protection against burning, as the ash that remains are materials that do not evaporate, limiting the concentration of flammable gases [2]. It is often mentioned that the main reasons for the high flame resistance of PVC based materials are the high concentration of halogens and the tendency to char. However, Martel's studies show that PVC can enable stable series arcing and ignition for the same reason [2].

Table 10: Resistance of PVC and PEX insulated electrical cables to series arc and glowing [2].

Test	Property / Characteristic	PVC (70°C)	PVC (105°C)	PEX (125°C)
Series arc at 230 VAC, 5 A load	Ignition probability	90 %	100 %	0 %
	Time to form stable arc	7.5 s	13.6 s	-*
Series arc at 230 V DC, 4 A load	Ignition probability	100 %	100 %	60 %
	Mass loss per unit of energy	176 µg/J	149 µg/J	71 µg/J
	Proportion of ash formation	13 %	8 %	27 %
Glowing at 230 V AC	Visible change	Melting and smoke formation	Melting and smoke formation	No damage
	Ignition	Small flames near arc	Small flames near arc	None

*A stable arc was not formed

The conclusion is that a PEX insulated cable is significantly more resistant to a series fault compared to a PVC insulated cable. This is also pointed out in a SINTEF report from 2007, which states that insulation materials vary considerably with regard to the propensity to form carbonized paths. Cables are often insulated with PVC. Unfortunately, PVC is one of the least satisfactory plastics in terms of resisting the formation of carbonized paths and creep currents [5]. These findings coincide with claims previously made to explain the development of a series fault in cases where PVC insulation material has been used [19]:

- *"This work shows how glowing contacts and surface arcing can decompose PVC insulation, form ignitable gases, and that it is possible for the subsequent series arc to ignite, and burn insulation. Two conditions are identified that can create an overheated connection – a glowing contact and/or breakdown over a charred insulation surface".*
- *"It is shown that glowing contacts and arcing across char are two forms of overheating, caused by series faults, which can potentially initiate a fire".*
- *"Continuous bursts of ignited gases can be created from overheated PVC insulation created from glowing contacts with subsequent series arcing, or surface breakdown with subsequent series arcing".*
- *"This charring can deposit onto the copper wire making it a good thermionic emitter. Charring on the inside of the insulator surface, between the two conductors can also occur. A carbonaceous path between the contaminated conductors can result in intermittent arcing between cracks formed in the char on the insulation surface or directly across the contaminated conductors. Carbon, on the wire, heated by an arc initially formed from mechanical contact of the two conductors, continues to arc because of the thermionic emission properties of the carbon".*
- *"The overheated PVC insulation can decompose and produce ignitable gases. These gases can ignite with each half-cycle of subsequent arcing until the fuel source is removed or used up. Surprisingly, fires, due to the ignition of evolved gases, were started with currents as low as 0.9* A_{rms}*,".*

It has also been pointed out in several studies that PVC insulation with $CaCO_3$ filler has a unique failure mode in the sense that PVC is the only material that has a propensity to fail as a result of wet tracking in otherwise dry environments, since the material can create its own layer of moisture. It has been shown that wet tracking can occur at modestly elevated temperatures (around 110°C) under dry conditions [17][54][55]. Standardized tests of PVC have suggested that the material has good ability to resist wet tracking. But unfortunately, research studies have shown that the good results for resistance to wet tracking are a consequence of the way the IEC 60112 test is performed, and not an indicator of actual performance [17].

An NTNU master's thesis from 2000 investigated whether PVC insulated installation cable may be to blame for some of the cases where installation materials have been heated [56]. Long-term measurements were carried out to investigate whether migration of plasticizer and chlorine from the PVC insulation could lead to increased contact resistance in a connection with subsequent temperature increase. In one case, signs of increased temperature due to migration from the insulation were found at the same time as corrosion was found on the conductor and residues of plasticizer on the component. Furthermore, it was found that if the PVC insulation had previously been exposed to temperatures up to 70°C or more, the threshold for the same degradation and migration of chlorine was lower than before the temperature increase. It was observed that such migration could occur as low as 64°C if the cable had previously been exposed to a temperature higher than 70°C [56].

Based on the findings presented above, it appears that PVC insulation material almost acts as a catalyst for the development of a series fault for an electrical cable. This is attempted to be illustrated in Figure 12, where the series fault course of a PVC and PEX insulated electrical cable is compared. When a series fault occurs for a PVC insulated electrical cable, the thermal decomposition of the polymer material promotes a repetitive and progressive process, in which the dissipation of electrical energy and temperature continues to increase until a dangerous arcing situation occurs, potentially resulting in a fire. In comparison, a PEX insulated electrical cable will not be able to decompose to the same extent at elevated temperatures [41], which means that the course of the series fault is interrupted or significantly slowed down so that an insulation failure does not occur. The course will possibly end up in a state of thermal equilibrium, where the thermal energy emitted to the environment corresponds to the electrical energy dissipated at the fault location. Further research in this topic should be directed towards substantiating and expanding the study presented in Table 10, with the aim of investigating the theory presented in Figure 12.

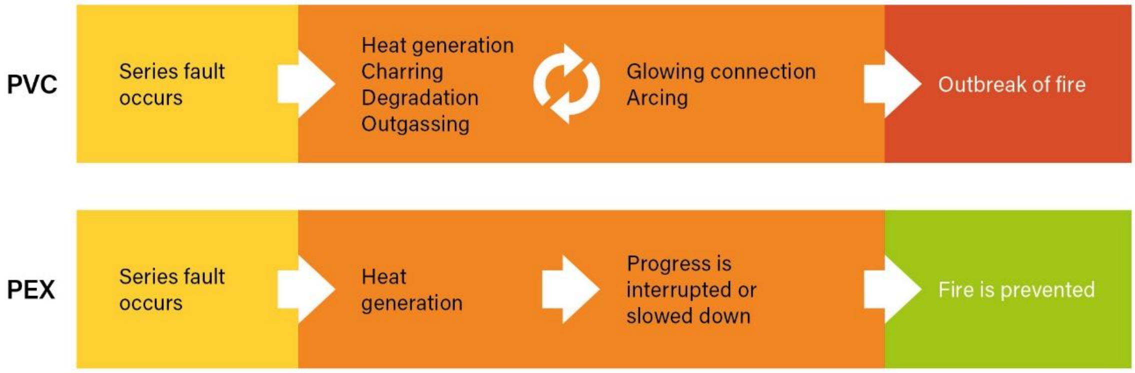

Figure 12: Series fault course of a PVC and PEX insulated electrical cable. In the case of PEX, the course of the fault could be interrupted, and the fire could be prevented.

5.4 Fires caused by the cable insulation material

5.4.1 Statistical occurrence

There has been a marked decline in the number of fire-related fatalities since DSB started such registering in 1979. During this period, more than 80 % of all fire-related fatalities have resulted from dwelling fires. Elderly people in need of care, people with disabilities and substance abusers are vulnerable groups. People over the age of 70, for example, have a four to five times higher risk of dying in a fire compared to the rest of the population. In the 5-year period from 2016 to 2020, an average of 38 people died annually in fire in Norway. Of 510 fatal fires in the period 2005 - 2014, electrical causes were registered as a cause of fire in 11 % of cases [38]. Similarly, in the period 2001 - 2003, a proportion of 9 % (electrical cause) of 185 fatal fires was reported [16]. This means that around 3-4 people are assumed to die annually in fires with an electrical cause. If it is assumed that about 1/3 of fires with electrical origin are caused by arcing, this suggests that 1 - 2 people may die annually in Norway in fires caused by arcing. In 2018, approximately 5000 building fires were registered, where around 20 % of these fires are registered with electrical cause. Assuming that around 1/3 of these approximately 1000 fires with electrical origin are caused by arcing, this suggests that arcing annually causes a few hundred building fires in Norway [10].

DSB's fire statistics indicate that both series faults (series arc) and electrical cables pose a significant fire risk in Norwegian buildings, in the sense that arcing causes a few hundred building fires annually, while wires and cables cause on average around 21 fires a year [6]. Weaknesses in the fire statistics have previously been pointed out in Norway, characterized by a high degree of underreporting (unreported cause of fire) and incorrect reporting (reported but unknown cause of fire). Furthermore, a fire cause report from the police is received for only about 67 % of building fires where the fire brigade has responded (numbers from 2022). If the remaining 33 % is unevenly distributed, this could be a significant source of error. Less than half of dwelling fires have historically been recorded with a causal category, suggesting that it is very often not trivial to determine the cause of the fire, perhaps especially in cases where electrical energy is identified as the source of ignition. In addition, factors such as a lack of resources and competence on the part of the agencies responsible for investigating and reporting cases may play a role [10]. DSB writes itself in a report from 2010 [57], which deals with statistics on fatalities in fires in the period 1986-2009, that "*throughout the period, it has been a problem that the fire cause category "unknown" has constituted a very high proportion, around 20 %. In order to try to improve this situation, complex investigation teams have been tested in recent years in parts of the country, consisting of representatives from the police, fire brigade and the Local Electricity Authority (DLE). In the long term, it is hoped that this will increase competence in fire investigation, and thus bring fire statistics to a higher level*".

Norwegian households have traditionally largely used electrical heat-emitting equipment, which can often lead to a persistently high load in consumer circuits. A series fault will therefore have the potential to result in a large power dissipation, which may result in an increased fire risk in Norway compared to other countries [14]. When comparing Norwegian fire statistics with corresponding fire statistics for other Nordic countries, some findings have been made that can be summarized as follows [21]:

- No more people die in fires in Norway compared to the other Nordic countries. The average number of fatalities per year per 100 000 inhabitants in the years 1999 - 2003 was 1.3 for Norway, 1.4 for Sweden, 1.5 for Denmark and 1.7 for Finland.
- There is no greater fire frequency in Norway compared to the other Nordic countries. The average number of fire call-outs per year per 1000 inhabitants in the years 2000 - 2004 was 2.7 for Norway, 2.9 for Sweden, 3.2 for Denmark and 2.5 for Finland.
- Electrical causes are a less frequently recorded cause of fatal fires in Sweden (3 %) compared to Norway (9 %), Finland (9 %) and Denmark (12 %).
- Norway has a relatively high proportion of registered dwelling fires with electrical cause (20 %) compared to Sweden (8 %) and Denmark (13 %).

Based on these findings, it does not appear that there is a particularly high fire risk in Norway, but it appears that registered dwelling fires in Norway more often have electrical cause compared with the other Nordic countries. As a possible explanation for this, the study mentions that electricity is less common as a heating source in Sweden, and that a larger proportion of the population in Sweden lives in blocks and apartment buildings where control of electrical installations may be to a higher standard than it is for other types of buildings [21]. It is nevertheless worth noting that the proportion of registered fires with electrical cause in Norway does not differ significantly from that registered in the EU or the UK, cf. Table 1.

A SINTEF report from 2012 on fire risk for electrical cables reveals the following related to cable fires and series arcs: [24]:

- *"Analysis of Norwegian fire statistics shows that the number of fires caused by electrical installation materials has had an increasing tendency. In 2009, 150 dwelling fires started in electrical installation materials, and this accounted for 4.5 % of all dwelling fires that year. Fires that started in cables make up a large proportion of these fires. Series arcing is the most commonly recorded cause of fire initiation in cables and installation materials."*
- *"According to a study of about 19 000 fires related to electrical installations in the United States, more than 40 % occurred in the wiring system (not specified). About 20 % occurred in sockets, and 18 % in branching wires".*
- *"From an analysis of 105 fires with electrical cause in the United States, it appears that cables and wires were involved in the start of fires in over a third of the fires".*
- *"The main electrical causes of fire are arcing, resistance heating, and exposure to external heat sources. Some examples of fires where cables have played an important role are presented in the report. Some of these fires have had major consequences in terms of personal injuries, property damage or damage to infrastructure".*

This last point has also been elaborated by Martel, who points out the following correlations for the severity of building fires with electrical cause [2]:

- *"The ICF reported that 13-20 % of all fires in Europe were caused by electricity. These fires seem to be particularly lethal because they accounted for 20 % to 30 % of the deaths (3250 per year) and injuries from all domestic fires".*
- *"The statistics from the CPSC are even more striking. The relatively small number (5 %) of all domestic fires caused by electrical distribution faults result in 28 % of the deaths".*
- *"On average, one life is lost in every 69 fires started in the electrical distribution; if the fires are due to other reasons, one life is lost in every 566 fires. Fires caused by electrical distribution faults are eight times more lethal than other fires".*
- *"Economic considerations produce a similar result: an electrical fire with costs on average $35500 compared with any other fire with average costs amounting to $5300".*
- *"The US Fire Administration reported that electrical fires are two times more lethal and cost 2.5 times more money than non-electrical fires".*
- *"One of the reasons mentioned to explain this result is the difficulty in detecting this type of fire and the greater chance of being surprised by a fire at night".*

The latter factor is corroborated by fire statistics from the USA in the period 1980-1981, which showed that 42 % of dwelling fires with electrical origin start in hidden, enclosed areas or usually empty, unoccupied rooms, while 17 % of the fires started in the bedroom. Significantly, the statistics also showed that the majority (73 %) of fires in enclosed areas occurred in cables and sockets [5]. Electrical faults in hidden/enclosed areas can in many cases develop for a relatively long period before the fire is discovered, either by residents or smoke alarms. Smoke can initially spread inside wall/roof structures, causing a hidden fire to spread in these areas. This can result in a delayed detection of the fire and it can therefore be more intense compared to an open fire [5].

5.4.2 Investigated fires

Several specific fire investigations related to insulation failure in electrical cables have been studied in more detail in this project. Documents have either been publicly available (on internet) or made available after granted access. Several examples have been found of cable fires caused by insulation failure, where the cable is stated to have PVC insulated conductors. A common factor for these cases is that there has been a thermal degradation and carbonization of the conductor insulator, which after some time has led to insulation failure (creep currents). Further developments have been glowing connections and/or arcing in the carbonized paths in the insulation material and ignition of a fire, without interference by the circuit breaker.

In the following, conclusions and statements from publicly available documents for three fires that had major consequences are presented, where the insulation material for an electrical cable may have been of significance for the fire in the initial phase.

Case 1: Fire resulting from an earth fault in a cable near a compressor:
On November 21, 1980, there was a fire at the MGM Grand Hotel in Las Vegas, USA. 85 people were killed in the fire, while more than 700 people were injured. The reconstruction work after the fire took 8 months and cost $50 million. In addition, there was a lawsuit settlement totaling $140 million. This is the second largest hotel fire in the mainland United States in modern times. The fire investigation was conducted by the Clark County Fire Department, the National Fire Protection Association (NFPA), U.S. Fire Administration and the National Bureau of Standards, and reports of the investigation have been made publicly available. The following findings were presented in the reports [58][59]:

- *"At approximately 7:10 a.m. on November 21, 1980, an employee discovered a fire in a bus station in a restaurant called the Deli at the east end of the Casino".*
- *"The Clark County Fire Department has determined that the most probable source of ignition was electrical in nature. This occurred within a combustible concealed space adjacent to a pie case along the south wall of the Deli".*
- *"In the opinion of the fire investigators (officers reporting), there is no question that a ground fault occurred. Improper installation and exposure to the warm* ***atmosphere surrounding the raceway caused the insulation surrounding the copper conductors to loosen and deteriorate, exposing the bare copper conductors****. Short circuit occurred in the exposed copper conductors because only two conductors existed (no ground)".*

An unfortunate placement of the supply cable (4 mm^2, which was retrofitted and not part of the original fixed installation in the building) for the compressor in the cooler caused the conductor insulation to be subjected to a permanently elevated temperature, and after 6 years of use, most likely, an insulation failure occurred due to a gradual thermal decomposition of the insulation material. The two supply conductors to the cooling counter were threaded through a corrugated tube made of aluminum, which at a point 1 m above floor level was in physical contact with a copper tube carrying refrigerant from the compressor to the cooler. At this point, galvanic activity may have occurred that has created a hole in the corrugated pipe and exposed the conductor insulation to hot air from the compressor. The heat dissipation from the compressor's condenser coil was stated in the report to be in the temperature range 49 – 82°C. The compressor was constantly active except for a de-icing cycle that lasted 15 minutes once a day. Inadequate convection of heated air around the compressor contributed to elevated temperatures in the hidden space in which the supply cable was located [58]. It is stated in the report that the cable insulation material was unknown, but it is also stated in the report that a 2.5 mm^2 conductor with TW-type insulation (PVC) should not exceed 60°C in normal operation [58]. There is a high probability that the supply cable was PVC insulated. The corrugated aluminum pipe was designed to be a conductor to earth, i.e. there was no separate earth conductor threaded through the corrugated pipe. Unfortunately, this aluminum tube was insufficiently connected to earth at the junction box, i.e. it was a relatively high impedance to earth. When the copper conductor came into contact with the corrugated aluminum pipe, this pipe became part of the voltage-applied circuit with the result that the pipe quickly became glowing hot and ignited surrounding materials [58].

Case 2: Fire resulting from an arc in the internal wiring of a ceiling lamp:
On 5 September 1986, there was a fire in Hotel Caledonien in Kristiansand, Norway. 14 people were killed in the fire, while 54 people were injured. The total insurance payments after the fire amounted to NOK 366 million (adjusted to 2010) [60]. In January 1987, a 125-page report on the fire was published, prepared jointly by The Norwegian Directorate for Civil Protection (DSB) and he Norwegian Building Authority (DiBK). The following statements about the fire were presented in the report [61]:

- *"The fire was alerted at 4:40 a.m. One night porter thought he had smelled smoke when he cleared the tables at Balustraden about 4:30 a.m".*
- *"The investigation carried out by The National Criminal Investigation Service (Kripos) with regard to the cause of the fire concludes that everything indicates that the fire occurred as a result of an electrical fault in a lamp in the ceiling above the access door to the restaurant Veteranen downstairs".*
- *"There were 2 identical lamps installed in the ceiling. The lamps were installed in 1973".*
- *"It is believed that the direct cause of fire was an electric arc.* ***The arc occurred in connection with the internal wiring in the lamp, either due to a breakage in one of the conductors or due to poor contact in the conductor's connection to the lamp holder****. The arc undoubtedly had a sufficiently high temperature to burn flammable material nearby. The fire probably started as a smoldering fire. The breakage or poor connection may have occurred as a result of constant vibrations in the ceiling when the door to the Veteran restaurant was opened and closed".*
- *"Between the ceiling to which the lamp was attached and the concrete deck there was a cavity. The smoldering fire, which went on for some time, developed flammable gases that filled the cavity. After some time, a local flashover occurred in the cavity and an open flame fire was a fact".*
- *"Underneath the ceiling were large quantities of electrical cables with plastic insulation. The plastic insulation on the cables consisted largely of PVC and undoubtedly contributed greatly to the development of smoke, and also to the formation of hydrochloric acid vapor".*
- *"It was ascertained that the fuses for the circuit on which the lamps in the entrance to the restaurant the Veteran were connected had triggered during the fire".*
- *"All indications are that the fire occurred as a result of an arc in a wire near a lamp downstairs".*

The lamp in question (incandescent) and the identical neighbouring lamp were examined by NEMKO (Norges Elektriske Materiellkontroll) at Kripos shortly after the fire. The following was documented in the report, dated September 25, 1986 [62]:

- *"The remains of the recessed incandescent lamps, as well as findings believed to be connected with these, have been examined during visits to Kripos".*
- *"The fixtures were mounted to the ceiling with three screws and a flexible wire was used for connection to an earthed electrical outlet mounted in a box for concealed system fixed to the ceiling above the fixtures".*
- *"The lamps are of product Arnold Wiigs Fabrikker (later Høvik Lys) type 7190 G, for max. 100 W incandescent lamp. The lamp was approved in 1967 and, according to information from the manufacturer, went out of production by 1983".*
- *"Internal wiring on the lamp, from the main connection box at the top of the lamp to the lamp holder's coupling screws, has been carried out with 2 wires of type TG 170 (silicone insulated with fiberglass braiding). Of these wires, one was found connected to a partially melted bushing clamp (from the lamp holder). The damage to the clamp is clearly a consequence of external heat exposure. The bushing clamp from the second connection in the lamp holder was not found, but this wire, which was found stuck on the lamp (of solidified silumin/aluminium), had traces indicating that there has been a series arc as a result of a breakage of the conductor, or due to poor contact in the connection to the lamp holder".*

- *"Of the lamp holder and light bulb, only small remnants remain. According to crime scene investigators, the same applies to the box (silumin) for the concealed system and the electrical outlet that had been installed in it".*
- *"Furthermore, in the fire debris, residues of flexible wire were found, fitted with parts from the plug, which is believed to be supply to the fixture. No traces were found on any of these components that could provide clues as to the cause of the fire".*
- *"The second fixture was somewhat less damaged. Of the internal wiring connections, one was still in place in the bushing clamp in the holder, while the other bushing clamp had come loose. It may be noted, however, that relatively large quantities of lint, possibly insulation materials, were found in the junction box of this lamp, without any explanation as to where this comes from".*
- *"From the investigation we must assume that the hotbed of the fire is to be found in relation to the series arc in the most damaged lamp. A series arc produces a very high temperature at the fault location, a temperature that in some unfortunate cases can ignite surrounding easily combustible materials".*

With regard to the surrounding easily combustible materials mentioned above, it is not clear from the crime scene investigation or NEMKO's report which materials could be ignited or could have contributed to ignition. The structure of the lamp and the materials used in its construction were not described, but pictures taken of the incinerated lamps show that the junction box (made of metal) was placed on top of the lamp, directly above the lamp holder itself. The internal wiring of the lamp was routed from this junction box down to the lamp holder and had silicone rubber insulation, possibly rated for temperatures up to 170°C, based on the naming of the cable type [62]. Silicone rubber generally has an ignition temperature of around 450°C. The supply line to the lamp was most likely PVC insulated, as it was pointed out that there were large amounts of electrical cables with PVC plastic insulation under the ceiling [61]. This supply line was inserted into the lamp's junction box, and thus there is reason to assume that there was PVC plastic in close proximity to the point where the series fault (contact failure) occurred. Elevated temperatures may have occurred inside the junction box as a result of the series fault. Photographs were taken of traces of arcing in the supply line of the lamp, as well as the aforementioned internal wire that had melted onto the fixture, but unfortunately the fire investigators' assessments of these arc traces were not adequately documented in the reports. Based on a review of the documents from the fire investigation carried out in 1986, it has not been possible to determine whether PVC plastic may have had a decisive impact on the development of the series fault that caused the fire in Hotel Caledonien.

It may be added that the fire in Hotel Caledonien has remarkable similarities with the fire in the MGM Grand Hotel six years earlier:

- The fires had an electric ignition source.
- The fires occurred at ground level inside a tall building where many people were sleeping.
- Within minutes, the entire 1st floor was torched, largely due to unfortunate material choices in both interior cladding, wall decorations and fixtures.
- Important building infrastructure was put out of action in the initial phase of the fire.
- Smoke spread upstairs through stairwells and shafts, preventing the evacuation of overnight guests via the internal escape routes.
- Survivors were rescued through windows using helicopters, and the rescue operation lasted for many hours.
- Almost all the victims died as a result of smoke or carbon monoxide poisoning.

The fire in the MGM Grand Hotel in 1980, as well as another hotel fire (the Las Vegas Hilton) three months later, had a major impact on fire safety in the United States. Among other things, hotels required fire sprinkler systems, automatic fire alarm systems, and overpressure in elevator shafts and stairwells to prevent smoke from spreading. Similarly, the severe fire in Hotel Caledonien had a major impact on the design of similar buildings in Norway. Among other things, a number of measures were introduced to prevent the spread of fire, to improve early warning systems, to improve evacuation conditions, and to improve the emergency preparedness capabilities of building personnel.

Case 3: Fire resulting from contact failure and subsequent ignition of wire insulation:
On June 14, 2017, there was a fire in Grenfell Tower in London, England. 72 people were killed and 74 people were injured in the fire. The total cost of the fire was estimated at £1.2 billion. This was the worst residential building fire in the UK since World War II and attracted international attention. Documents from the fire investigation were made public in November 2018 and are available online. From the documents it appears that the fire started at the 4th floor in a Hotpoint FF175BP fridge/freezer cabinet (manufactured by Whirlpool) due to a poor crimp connection (series fault), cf. Table 3 - improperly performed coupling creates a contact failure. The fridge-freezer was manufactured in October 2008 and had a rated power of 120 W (maximum 190 W) at 220 - 240 VAC. The fridge-freezer's power cable had an internal 13 A fuse in the plug and was of type H05VV-F [63] with both PVC conductor insulation and outer sheath and 21-wire copper conductors with a total conductor cross-section of 0.75 mm^2.

The fire investigation, led by Dr. John Duncan Glover at Failure Electrical LLC, suggested the following sequence of events for the fire [64]:

- "*Insulation on an energized internal wire within the compressor relay compartment ignites due to an overheated, poor crimp connection: Exhibit JDG/6B*".
- "*Fire and heat from the fire melts and burns off the insulations on the internal wire as well as adjacent wires, resulting in a short circuit (arc fault) from the energized wire across the run capacitor wires in the compressor relay compartment: Exhibit MJS/1*".
- "*The short circuit/arc fault is sufficient to trip the 32-ampere miniature circuit breaker (MCB) for Circuit No. 7 (Kitchen) without a blown fuse in the plug for the fridge freezer power supply cord (mains supply flex). Localized temperatures in the vicinity of the arc fault are well in excess of the melting point of the copper wires (approximately 1080°C/1980 °F)*".

The short-circuit/parallel arc from phase conductor to neutral conductor, which was detected with exhibit MJS/1, is most likely secondary, i.e. it occurred after the conductor isolation had been burned off. It is not clear from the investigative documentation whether at an earlier stage there was formation of series arcs inside the poor crimp connection or parallel arcs between live conductors in the compressor relay compartment as a result of creep currents in carbonized paths in the conductor insulation. The report states that the only wires found with arc damage that could have tripped the automatic circuit breaker (MCB) for circuit no. 7 were exhibits MJS/1 and JDG/1. Exhibit JDG/1 had likely been arc damaged at an earlier stage and was not related to the fire. It may be added that in the investigation report [65] it is pointed out that the cause of the fire (poor crimp connection) published in the fire investigation report was strongly challenged by Whirlpool (the manufacturer of the fridge-freezer) without new expert evidence being provided, while the head of the investigation has stated that it is not possible within the scope of the investigation to identify with certainty the exact nature of the fault in the fridge-freezer that caused the fire.

The PVC insulated conductors in the supply cable for the fridge-freezer together with other internal power conductors were fed into the compressor relay compartment. It is highly likely that all internal cables in the fridge-freezer were PVC insulated. This means that PVC plastic was in close proximity to the poor crimp connection (exhibit JDG/6B) where the heating had taken place, most likely ever since the fridge-freezer was first used. The compressor relay compartment was of type BRPT2101-3 and made of polyphenylene-oxide (PPO) plastic. PPO is a halogen-free semicrystalline thermoplastic polymer with a high glass transition temperature (T_g > 200°C) which makes it resistant to thermal deformation [66]. Plastic used in the relays themselves is typically halogen-free. It is therefore reasonable to assume that thermal decomposition (outgassing) and carbonization of the PVC insulation in the compressor relay compartment may have had a significant impact on the course of this series fault.

The investigation report states that connections exposed to prolonged high temperatures may experience an accumulation of an oxide layer, which gradually increases contact resistance with subsequent increase in temperature. Prolonged overheating can ignite nearby wire insulation [64]. The thermal decomposition of the PVC insulation that occurred when the conductor or ambient temperature exceeded 70°C may have resulted in the outgassing of both corrosive gases (HCl) and flammable (flammable) gases, including hydrogen gas [19]. The corrosive gases may have contributed to accelerated oxidation of the metal in the crimp connection with a subsequent increase in contact resistance, while the presence of combustible gases from the PVC decomposition may have been the trigger for the ignition. The minimum ignition energy from a spark or arc discharge needed to ignite an air/fuel mixture varies between 0.1-0.3 mJ. For hydrogen, on the other hand, it is significantly lower, around 17 µJ. In comparison, a 0.2 A half-cycle for an arc, even at a minimum arc voltage of 10 V, produces an energy of about 16 mJ, which is more than enough energy to ignite the combustible gases released when PVC is heated [19]. The rated power consumption for the fridge-freezer in question was 0.5 A, and both a compressor starter relay and an overload relay were located inside the compressor relay compartment. Arcing can occur in a relay when the contacts are opened and closed.

An alternative causal relationship for the fire at Grenfell Tower may therefore be:

- The cause of the series fault was a poor crimp connection (exhibit JDG/6B) in the compressor relay compartment.
- The reason why the series fault developed into ignition of a fire was the thermal decomposition of the PVC insulation on the live wires in the compressor relay compartment with subsequent outgassing of flammable and corrosive gases.

5.4.3 Commentary on fire investigators' crime scene investigations

Based on the crime scene investigations that have been reviewed in this project, it appears that both Norwegian and international fire investigators have a good understanding of the connection between thermal decomposition (charring) of the insulation material and subsequent insulation failure (abnormal current paths). These are clues that an experienced fire investigator apparently readily recognizes at a crime scene investigation. In the document NFPA 921, *Guide for Fire and Explosion Investigations*, first published in 1992 with the intention of establishing guidelines and recommendations for the safe and systematic investigation or analysis of fire and explosion incidents, impaired insulation properties of PVC are covered [67]. Among other things, the semiconducting properties of charred conductor insulation, overheating of insulating material near a weakened electrical connection (contact failure) and thermal degradation of the conductor insulation by overload (too high current in the conductor) are described. It is explicitly mentioned (in section 9.9.4.5.1) that PVC insulation is susceptible to arcing across carbonized paths, and that PVC has a unique failure mechanism in that wet tracking can occur in otherwise dry environments (self-induced wetting). It therefore seems that the problematic properties of PVC have been well known to fire investigators for many decades.

Viewed in a broader perspective, however, it is concerning that this thermal decomposition is almost regarded as an inherent property of any insulation material, while in reality it is a known weakness of one specific insulation material, namely PVC. Why is it accepted that PVC exhibits such poor insulation properties when a series fault has started to develop in an electrical installation? In the investigations reviewed in this project, no statements from fire investigators have been found pointing directly to the central role PVC may have played in the initiation of the investigated fire.

Nor have there been documented findings in the fire investigation cases examined to suggest that the same causal relationship (i.e. thermal decomposition and charring of the insulation material with subsequent insulation failure and abnormal current paths) applies to PEX insulated electrical cables in low voltage electrical installations. It is therefore not unreasonable to assume that the course of the fault situations that have caused the investigated fires in the previous chapter could have been interrupted if the live wires had been PEX insulated. The arguments supporting this assumption are:

- Martel's study of cable insulation materials, cf. Table 10, suggests that PEX cannot be ignited either by a series arc at 5 A or a glowing connection [2].
- At temperatures below 400°C, PEX will not be subjected to thermal decomposition and outgassing of flammable and corrosive gases [41].

5.5 Active and passive protection against series faults

The regulation relating to low voltage electrical installations (applicable from 01.01.1999) are issued by DSB and regulate who can perform, repair and maintain electrical installations, and how the installation is to be performed. The purpose of the regulation is to achieve proper electrical safety in the design, execution, modification and maintenance of low voltage electrical installations and usage of electrical equipment connected to such facilities. The regulation define requirements for the qualification for contractors, safety, planning and execution, documentation, and electrical influences of the environment [68]. Chapter V of the regulation deals with safety requirements in the form of protection and other safety measures, and (in paragraphs 20-28) there are requirements for protection against:

- §20 - electric shock in normal use
- §21 - electric shock in case of failure
- §22 - harmful thermal effects
- §23 - over current
- §24 - stray currents
- §25 - over voltage
- §26 - under voltage
- §27 - voltage drop in the electrical installation
- §28 - external influences

It is specified that the norm describing how the safety requirements in Chapter V can be fulfilled is NEK 400, Part 2-8, with the amendments specified in Appendix 1 of the regulation. The guide to §22 states the following:

- *"Particular attention must be paid to the risk of high resistance in cable/wire termination points. This can lead to dangerous heat generation and, in some cases, fire. Such hazards may arise as a result of unsatisfactory attachment of the conductor or permanent load of the cable/wire up to the cable's maximum current capacity".*
- *"Designers/contractors must be particularly aware that such abnormal heat generation in contact points may cause insulation material to emit gases that are corrosive and may affect transition resistance over time. To prevent such hazards from arising, the adaptation between overload protection and the current carrying capacity of the cable must be carefully considered."*
- *"When stripping insulation, it is particularly important to use suitable tools that do not damage the conductor material of the cable/wire."*

The regulations also specify that when using PVC insulated cable with a cross-section up to and including 4 mm^2, protection against overload shall be chosen so that the highest test current I_2 of the protection does not exceed the maximum current carrying capacity of the cable I_z or the highest test current I_2 of the protection does not exceed the highest test current used for material in the circuit. This is further specified in chapters 431.3, 705.4 and 823.4 of NEK 400:2022.

In other words, in an electrical low voltage installation, there are requirements for the implementation of various measures to reduce the risk of fire. In practice, this means that both passive and active protection are applied. Conventional active protection devices can include earth fault relays, circuit breakers, and surge protectors, all of which are normally placed in a distribution cabinet. Fire statistics indicate that series faults are a prominent cause of fire in Norwegian buildings, which means both that series faults occur frequently in low voltage electrical installations and that such conventional protection apparently does not adequately capture series faults with subsequent glowing and arcing. In recent years, various devices have therefore been developed that can actively detect and prevent the development of a series fault in a low voltage electrical installation. These include arc fault detection devices (AFDDs), cable gas detectors, infrared thermography, and various forms of local heat detection [14].

NEK 400:2022 specifies in Chapter 428 that for electrical installations in areas where irreplaceable assets are stored (museums, historic buildings, libraries, and document centers), measures shall be provided for protection against fire caused by insulation failure and series faults. In areas intended for sleeping people (bedrooms), it is recommended to take measures for protection against series defects in consumer circuits in accordance with Chapter 424, which specifies that measures shall be put in place to disconnect the course when a series fault is detected. In AC courses, an AFDD in accordance with EN 62606, located at the start of the circuit, can satisfy the requirements for such disconnection. The primary function of an AFDD is to protect against dangerous arcing in an electrical installation. The AFDD must be installed at the start of the circuit it is supposed to protect. If a dangerous arc is detected by the AFDD, the power supply to the circuit will be interrupted, which applies to both series and parallel arcs. At the same time, the AFDD should ideally be able to identify harmless arcing that would normally be generated by consumer equipment, and in such cases the circuit should not be disconnected.

A comprehensive study by J. J. Shea on the conditions for series arcing in PVC insulated electrical cables from 2007 concludes as follows [19]:

- *"New methods are needed to mitigate the effects of low current series arcs and glowing contacts on electrical fires. This could include improved circuit protective devices for detecting arcs with resulting fire mitigation, together with better heat resistant insulating materials that do not easily produce combustible gases".*

The study points to a need for both active and passive protection against series faults. It is observed that most publications citing this study revolve around the development of arc protection technology, and it seems that research in this topic since 2007 has largely focused on developing technology for active protection. This research has often been conducted by large manufacturers of active protection devices for use in low voltage electrical installations. It can be speculated that economic considerations have made it more attractive to focus on active protection against series faults rather than passive protection.

In 2013, a European standard for arc protection (IEC 62606 - General requirements for arc fault detection devices) was published, which is a comprehensive 150-page document defining a number of requirements that an arc protection device must satisfy [69]. In this standard, the protection device's ability to detect arcs is tested in various ways, including the manufacture of carbonized paths in a cable sample, which is described in Chapter 9.9.2.6 of the standard. In general, the manufacture of stable arcs is very challenging to achieve. The preparation and use of such a cable sample enables testing of an arc protection system under reasonably controlled and reproducible conditions. The process of preparing a cable sample is described in detail in the standard, and it is emphasized that PVC insulated conductors must be used together with a PVC based insulation tape. It is further mentioned that the cable types SPT2 and H05VV-F are particularly well suited for this purpose. The reason why the test requires PVC based insulation material is most likely that it is difficult to make carbonized paths in most other cable insulation materials. One may ask whether it would have been possible to make such a cable sample using PEX based insulation material, and whether the real function and detection ability of an AFDD would be affected if there was no PVC insulation present in the electrical circuit.

In his doctoral studies, Martel explored the possibilities of reducing the occurrence of series arcs by implementing both active and passive protection, and some of the findings from this work are as follows [2]:

- *"The investigations on the insulation polymers provide evidence of a clear relationship between the tendency of many polymers, especially PVC, to produce conducting ashes at thermal degradation and to promote the initiation of stable series arcs at AC voltage. In contrast, PE and other halogen-free polymers are very resistant against series arcing".*
- *"**Using arc-resistant polymers as insulation for wiring and other electrical parts would lead to a great improvement in electrical safety**. Nevertheless, the gains in safety must be weighed against possible disadvantages that this measure could bring. The polymer PVC is widely used in electrical equipment not only due to the lower costs, but also because of its excellent chemical and mechanical properties".*
- *"The practical use of these arc-resistant polymers in the different electrical applications should be studied in terms of the costs and other technical requirements. These findings should be taken into account in installation and product standards".*
- *"As long as arc faults cannot be completely inhibited by passive safety measures, the use of active protection against arc faults, the AFDD or AFCI, is recommended. Further research efforts should be aimed at increasing passive protection from series arc faults".*
- *"A detailed and reliable investigation by the CPSC [SmCo87] on a small number of fires in the electrical distribution networks (149 fires in 16 U.S. cities) shows the high occurrence of electrical fires in older homes. A majority of fires occurred in houses older than 40 years. This means that prescribing protection devices such as RCD, MCB, or AFCI in new installations is a sensible initiative, but retrofitting older installations would also be highly recommended".*

Here, therefore, the use of arc-resistant insulation materials is pointed towards as an effective passive protection against series faults. At the same time, it is argued that PVC has low cost, good mechanical/chemical properties and is part of established practice. In the project, both Martel and Babrauskas have been contacted and asked for arguments that can explain why PVC is still widely used as a cable insulation material in low voltage electrical installations. In their response, both cited low costs combined with established practice as the most important (and only) factors.

Even if stricter requirements are introduced for the use of arc-resistant insulation materials for cables and other components in low voltage electrical installations in the near future, there will remain a lot of PVC in existing electrical installations for a long time to come, with the risk this brings with it for electrical fires. Further development of active protection against series faults therefore seems logical, especially if this technology can be made sufficiently good to constitute an effective fire prevention measure. It may be mentioned that various forms of passive protection against series faults in low voltage electrical systems have been tested. A SINTEF report points to a passive fire prevention measure in the form of a requirement for metallic tubes for the electrical installation in dwellings in Chicago (USA). The report presented the following statements [5]:

- *"Due to numerous and costly fires throughout history, the Chicago government has established strict rules for electrical installations and equipment. As shown in Figure 2.15, this has meant that the share of the cost of electrical fires in dwellings, of the total cost of dwelling fires, is substantially lower in Chicago, compared to the rest of the United States (i.e., nearly a quarter of the U.S. average)".*
- *"As shown in Figure 2.16, the corresponding cost estimates for fires due to electrical installations in Chicago are well under half of the corresponding figure for the rest of the United States".*
- *"An important reason is that for a long time in this city there has been a requirement for metallic tubes for the electrical network in dwellings. In this way, electrical wiring, which is the installation material that clearly causes the most fires in the electrical installations in dwellings, is effectively isolated from combustible material by means of a metallic barrier".*
- *"The fact that wires and cables are laid in metallic tubes is the only difference that can explain the fewer fires in the electrical installations in Chicago compared to the rest of the United States".*
- *"The experience in Chicago is that this practice has not resulted in appreciable increases in housebuilding costs compared to the rest of the country".*

Laying electrical cables in such metallic tubes provides increased protection against external thermal and mechanical influences, such as rodent damage or nail strokes. In addition, the measure means that old, deteriorating cables can be replaced in a simple and inexpensive way [5]. The experience from this specific measure in Chicago illustrates how effective such passive protection of electrical installation cables can be in preventing fires with electrical cause in buildings. This suggests that the use of arc-resistant insulation materials for electrical cables as passive protection against series faults is likely to be a good fire prevention measure.

6 Summary and recommendation

Building fires with electrical cause are a recurring theme in Norwegian and international fire statistics. This type of fire turns out to have a higher cost, both in terms of the number of fatalities and loss of material values, compared to other types of fires, which implies that measures that can reduce the occurrence of fires with electrical cause have particularly high value to the society. In Norway, around 3-4 people are estimated to die annually in fires with electrical cause. In DSB's fire statistics, the causal category "series arc" is large, with a share of around 35 % of all dwelling fires with electrical cause. This indicates that series arcing occurs frequently in Norwegian low voltage electrical systems. In this work, the series arc is considered to be part of the course of a series fault, since arcing, like resistance heating and glowing connections, is seen as part of the course of a series fault. The mechanisms involved in the arcing process are complex, and investigations of various fault scenarios have demonstrated that a series fault in an electrical installation has a high complexity.

In Norway, PVC plastic is used extensively in low voltage electrical installations, primarily as a cable insulation material. PVC insulated electrical cables have an E_{ca} classification in the Construction Products Regulation (CPR), and NEK 400:2022 allows the use of cables with an E_{ca} classification in most applications, including dwellings. The thermal decomposition of PVC is problematic and causes the insulation properties of PVC to deteriorate at elevated temperatures. The decomposition also leads to the outgassing of many different flammable gases. A number of research studies indicate that PVC has a very adverse effect on the course of a series fault due to the elevated temperatures that occur in such a fault situation. PVC is one of the least satisfactory polymer materials in terms of resisting the formation of carbonized paths and creep currents. This connection has been strengthened by the review of several specific fire investigation cases where PVC insulation appears to be a contributing factor, and often crucial, for a series fault developing into the ignition of a fire. There are strong indications that a thermally stable and arc-resistant cable insulation material can significantly reduce the risk of a series fault in a low voltage electrical installation developing into a fire.

Based on the findings in this literature review, it appears problematic from an electrical safety perspective that PVC is still permitted to be used as insulation material in low voltage electrical installations. Most of the reviewed documentation points to phasing out PVC as a logical measure, primarily from an electrical safety perspective, but also for environmental and health reasons. There are already alternative insulation materials in the market that are thermally stable and economically competitive compared to PVC. An example of such an insulation material is cross-linked polyethylene (PEX), which is a halogen-free thermoset plastic material developed over 50 years ago. It is recommended that a review of the requirements for electrical cables and their applications be made at the next revision of NEK 400. The reaction of a cable to fire should not be the only criterion for determining its application. The electrical safety aspect must be emphasized, especially when it can be demonstrated that the use of PVC insulation material brings along an increased risk of an electrical fire occurring.

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